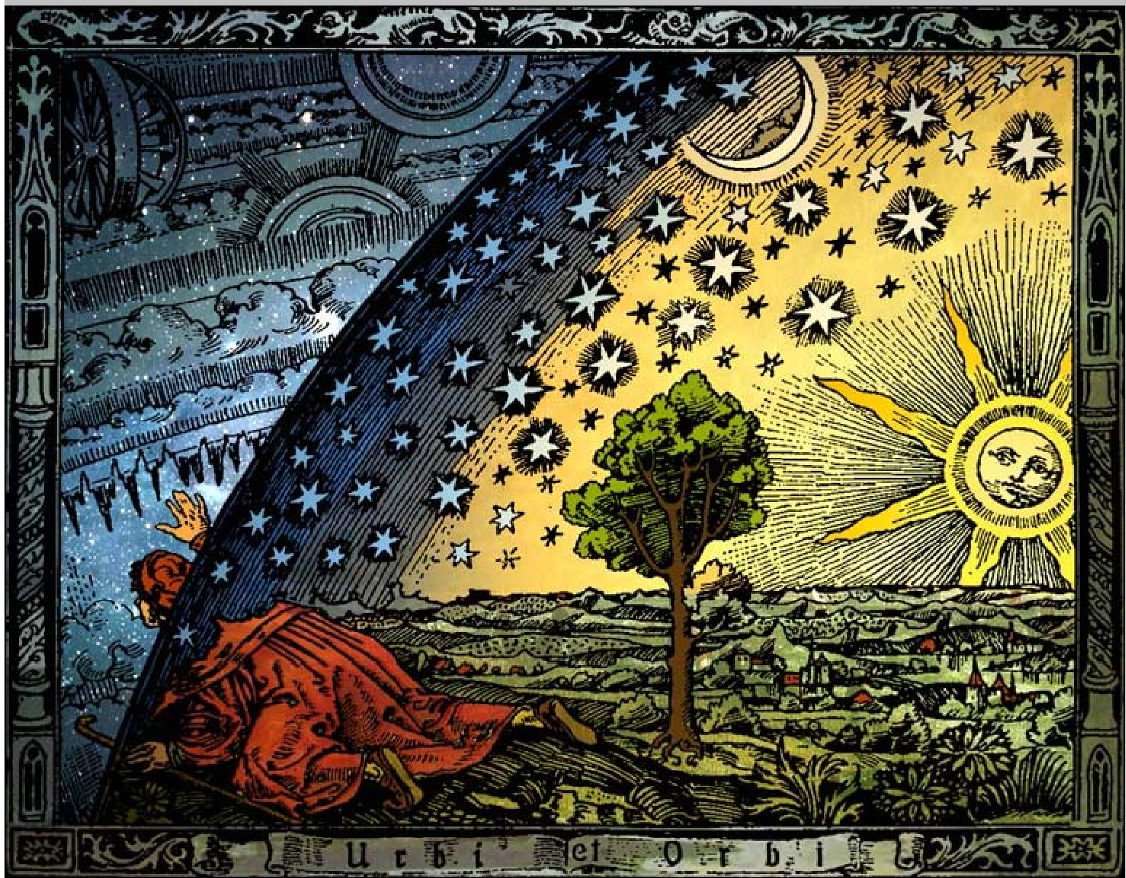
Stepping stones across the dripline

EURORIB 2012
20120524, Abano Terme

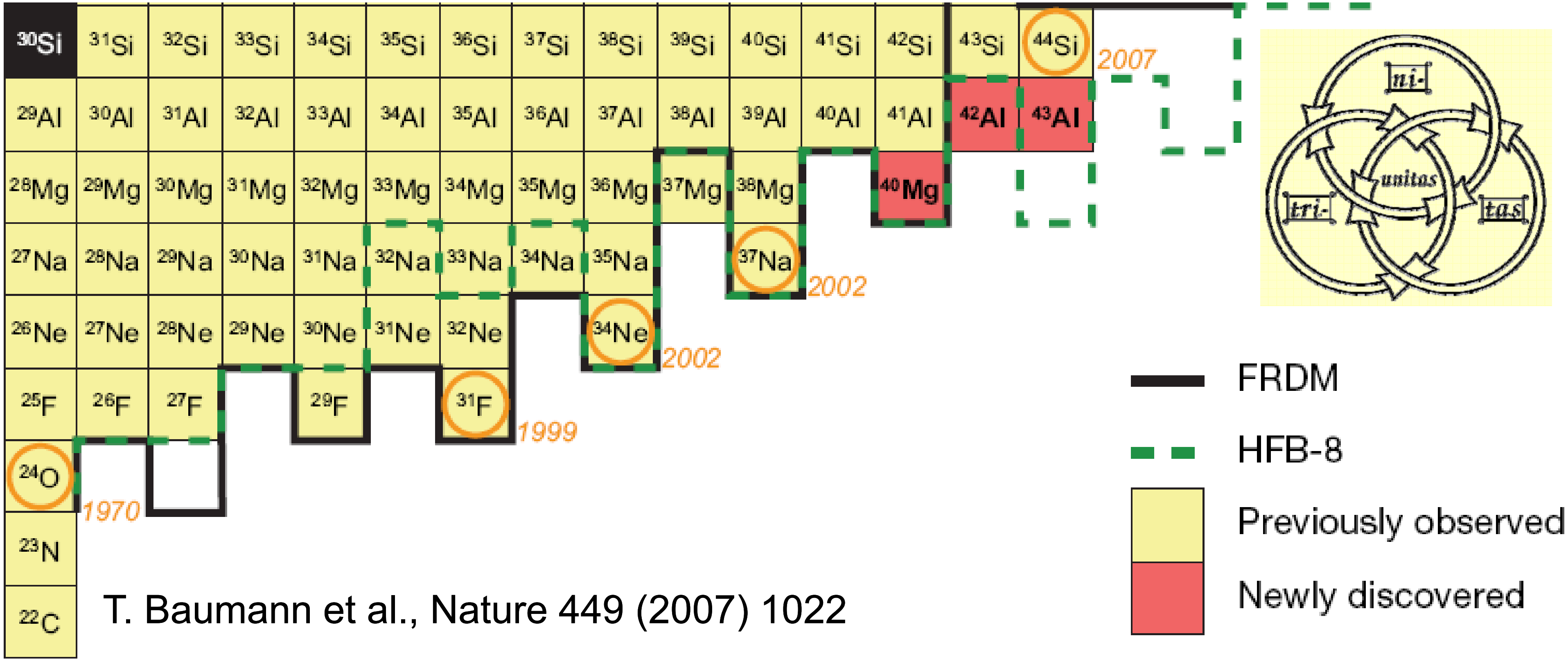


H. Simon • GSI Darmstadt

Menu

1. Tools
2. Extremely neutron rich systems: $^{12,13}Li$
   - remnants of halo nuclei
3. The puzzling structure of ^{14}Be via ^{13}Be
4. Steps towards FAIR
5. Summary

At the boundaries: Three body correlations



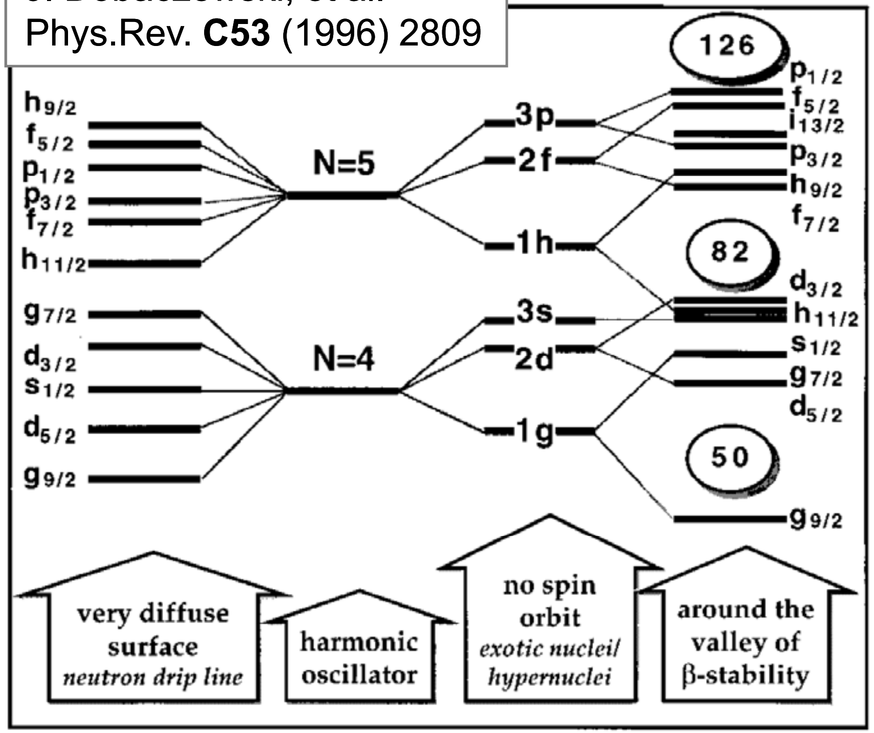
T. Baumann et al., Nature 449 (2007) 1022

Nuclear structure for extreme N/Z ratios

Mean-field modifications

- **surface composed of diffuse neutron matter**
- **derivative of mean field potential weaker and spin-orbit interaction reduced**

J. Dobaczewski, et al.
Phys.Rev. **C53** (1996) 2809



Nucleon-nucleon interaction

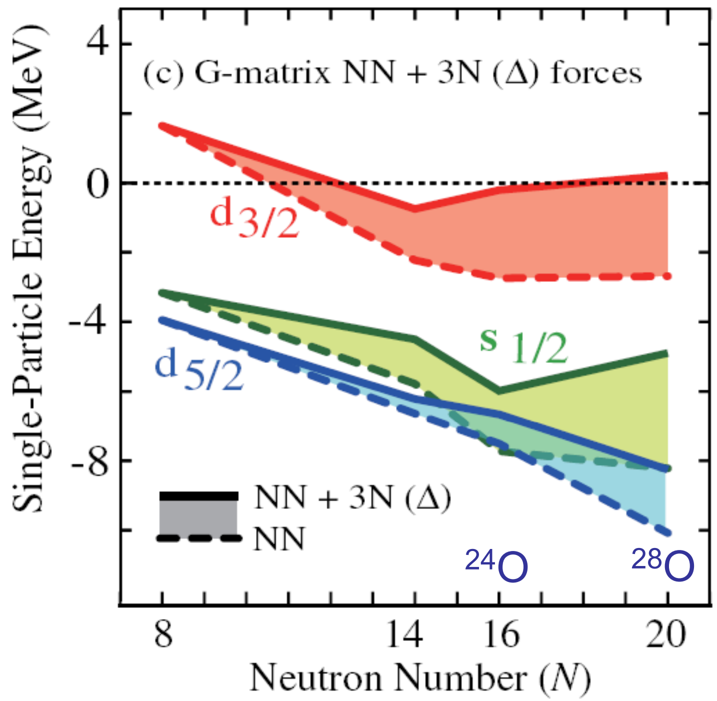
- **$\sigma\sigma\tau\tau$ interaction :**
  coupling of p-n spin-orbit partners in partly occupied orbits

O: missing $\pi d_{5/2}$ do not bind $\nu d_{3/2}$ → N=16

T.Otsuka et al.,PRL**87** (2001) 082502
(tensor) PRL**95** (2005) 232502

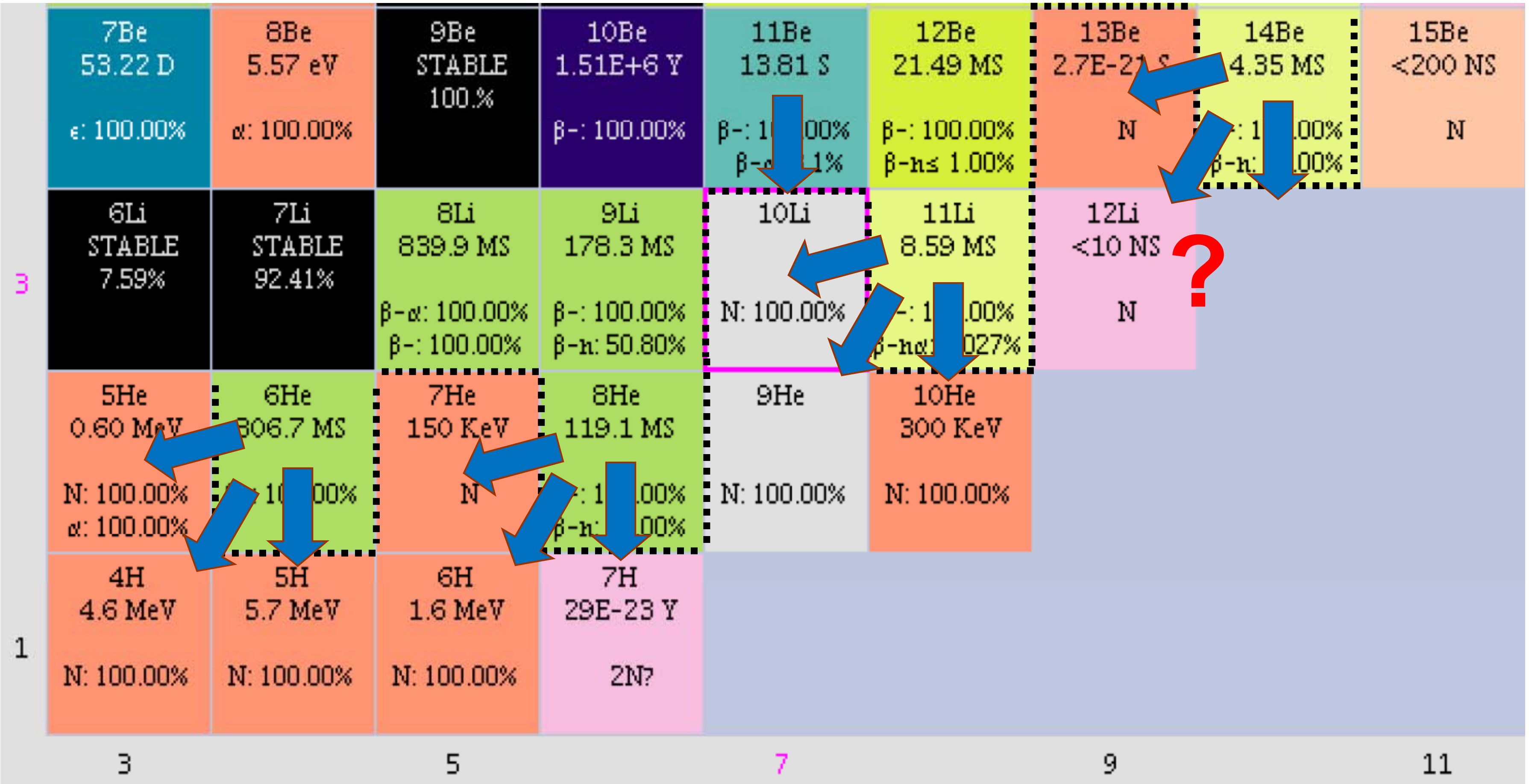
- **Repulsive 3N force**

T.Otsuka et al., PRL**105** (2010) 032501



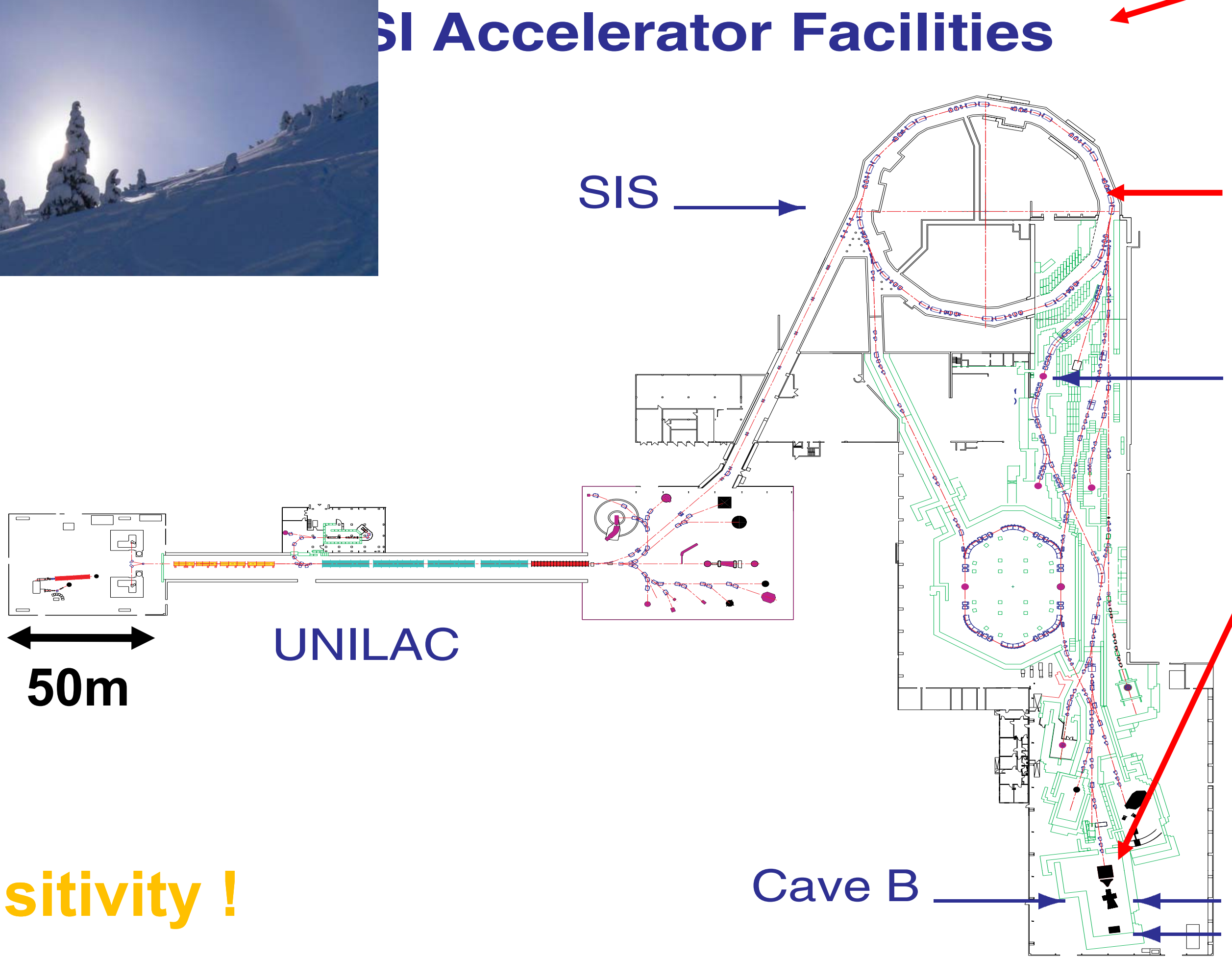
Exotic structure across the dripline

P.G. Hansen, Nature 328 (1987) 476



Clean & unbiased production

Boundary conditions for spectroscopic studies



primary beam
~ 0.5 GeV/u
~ 10^{10}/s

production target

secondary beam
~ 10 – 1000 /s

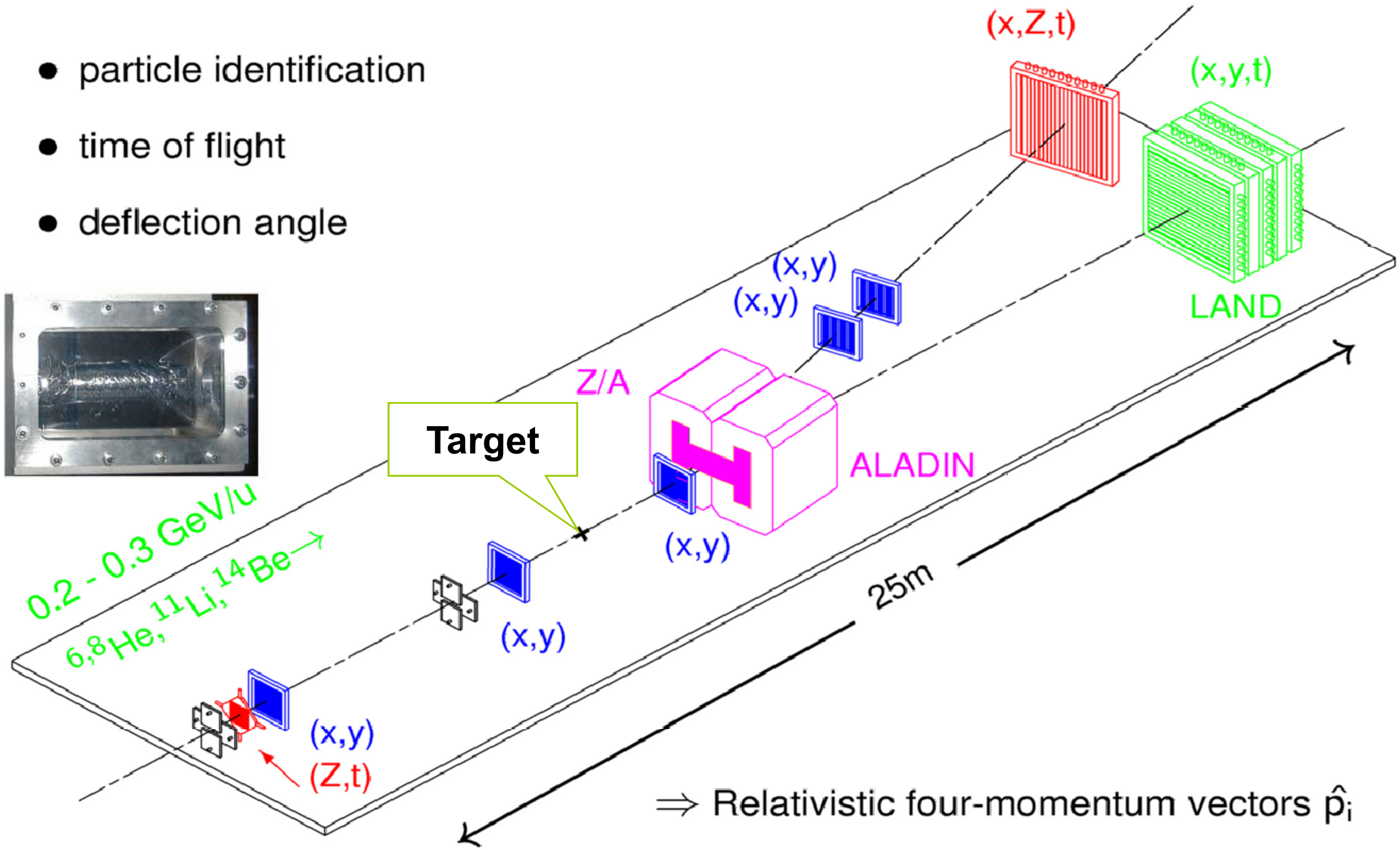
reaction target
~ 1%,
~ 1g/cm² C

"ternary beam"
~ 0.1 – 10 /s

➔ Sensitivity !

Experimental Setup (kinematically complete)

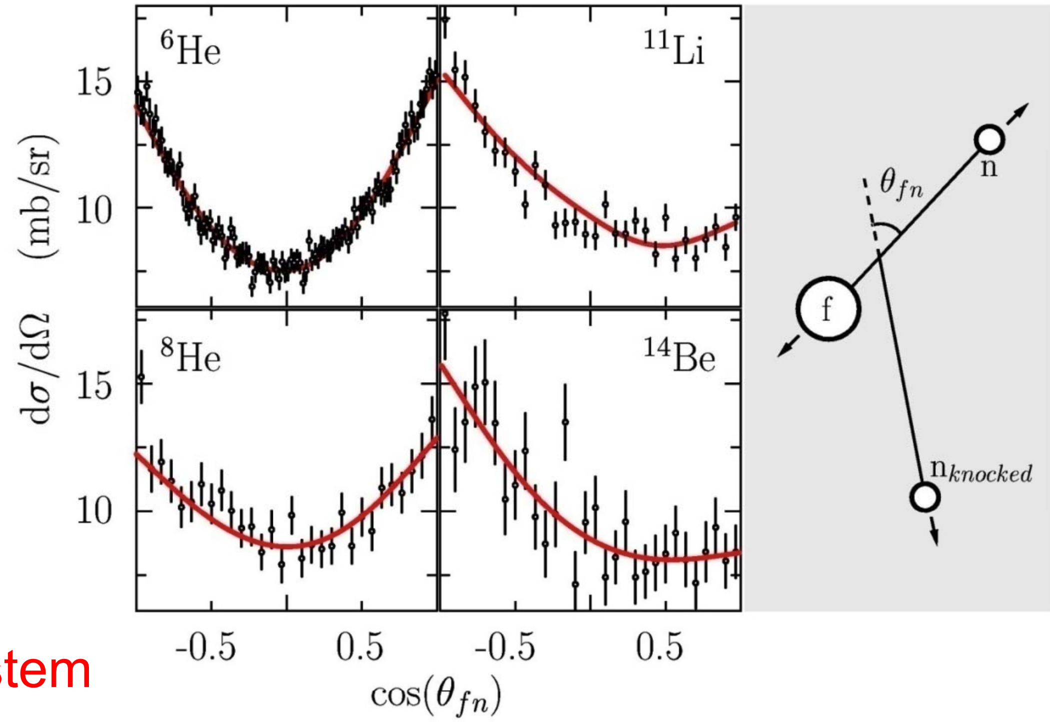
- particle identification
- time of flight
- deflection angle



⇒ Relativistic four-momentum vectors $\hat{p}_i$

Intermediate system tells g.s. properties (knockout)

Observables:



Momentum knocked out neutron

missing momentum

CMS: $\mathbf{p}_m = -\mathbf{p}_{n2} = \mathbf{p}_{n1} + \mathbf{p}_f$

Spectroscopy of intermediate system

relative energy

CMS: $\mathbf{p}_{fn} = \mu/m_n\, \mathbf{p}_n - \mu/m_f\, \mathbf{p}_f$

$E_{fn} = p_{fn}^2 / 2\mu$

Angular correlations (momenta)

$$\cos(\theta)_{fn} = \frac{\mathbf{p}_m\, \mathbf{p}_{fn}}{p_m\, p_{fn}}$$

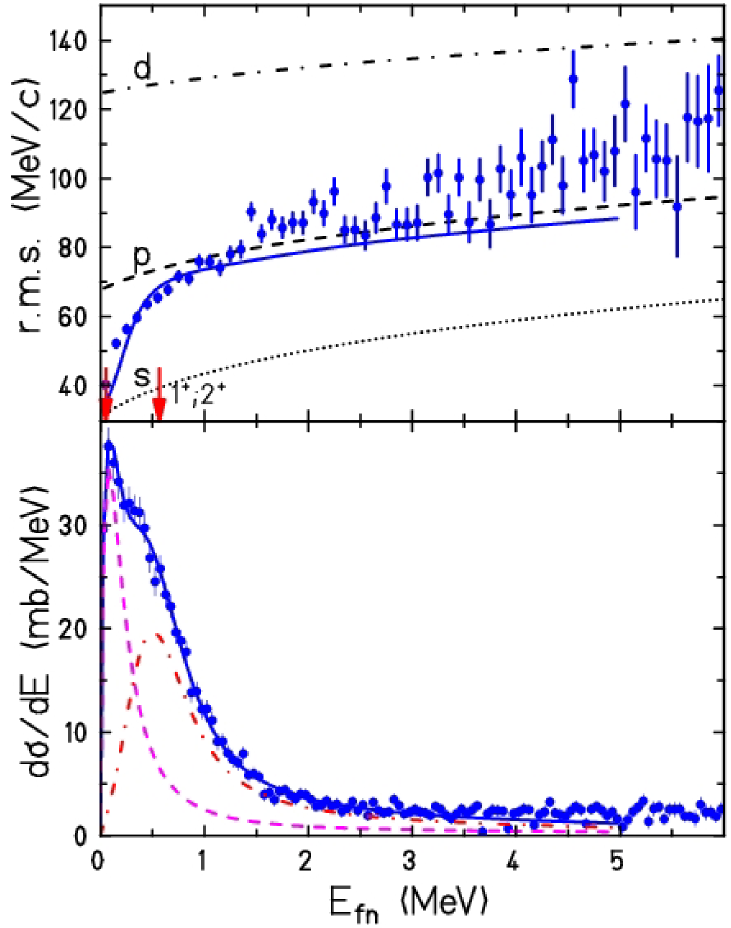
Sensitive novel approach: Momentum profile

^{10}Li	^{11}Li

Transverse momentum
Distribution of ^{10}Li
(missing momentum)

Decomposition and position of
s and p confirmed!

similar result with energy
dependent angular correlations



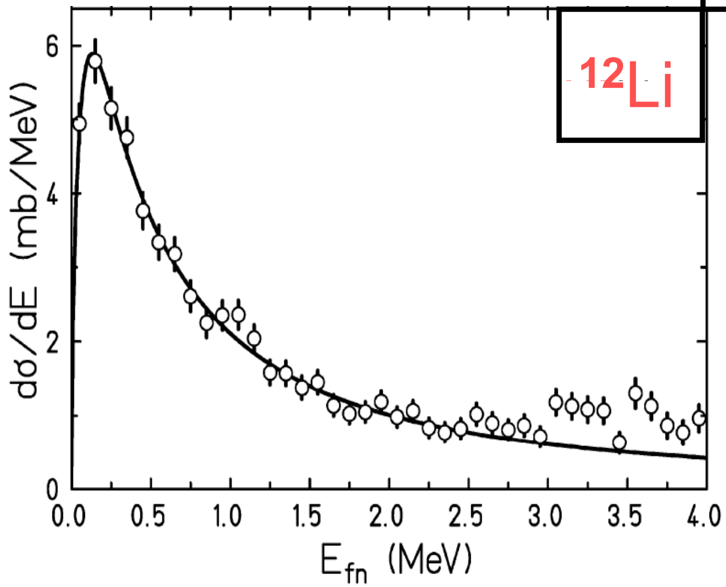
Y. Aksyutina et al.,
submitted

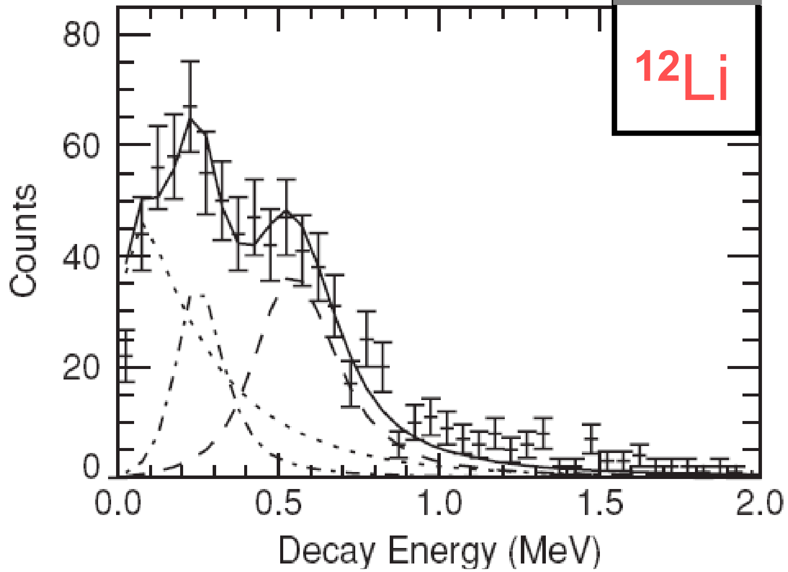
Exploring Unbound Lithium isotopes

^{14}B

^{14}Be

^{12}Li



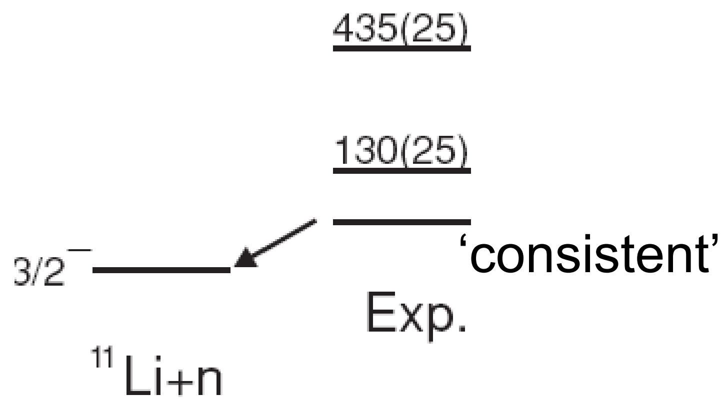


^{12}Li

Bertsch, Hencken, Esbensen, PR**C57**(1998)1366

a_s (fm)	S_n(MeV)
-13.7(1.6)	1.47(0.19)

Close to S_{2n} ^{14}Be



Y. Aksyutina et al., PL**B666** (2008) 430

C. Hall et al., PR**C81** (2010) 021302

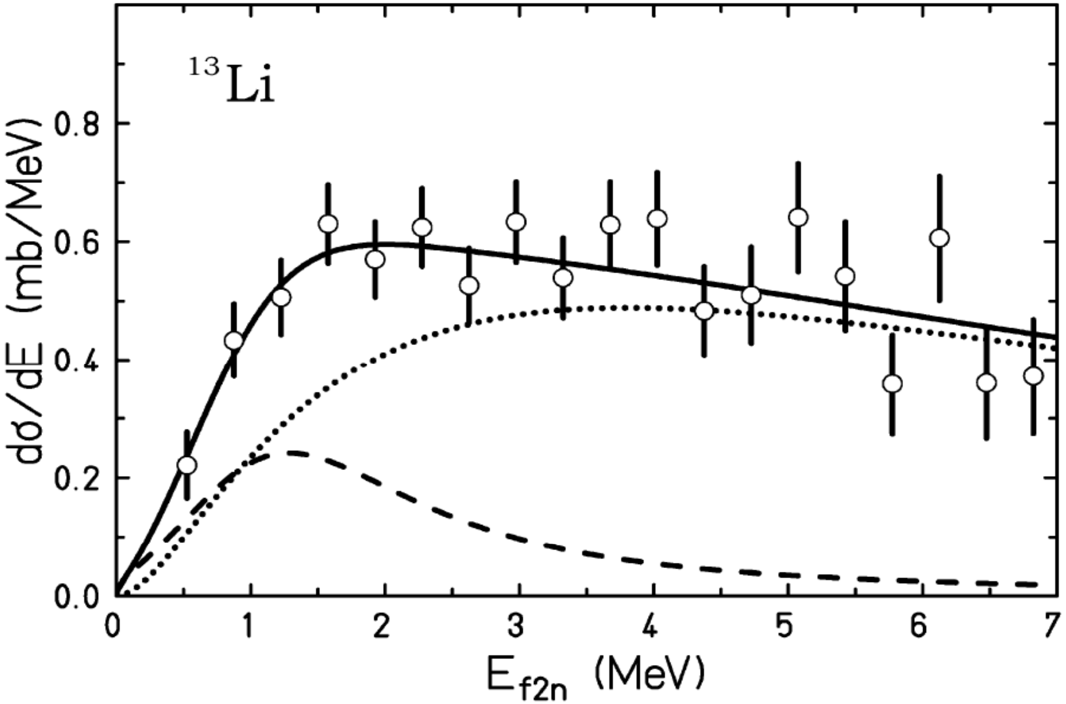
Exploring Unbound Lithium isotopes

^{14}Be
^{13}Li

^{13}Li: ^{14}Be + p → ^{11}Li + n + n

$d\sigma/dE_{noFSI} \propto E^2/(2.21\ S_{2n} + E)^{7/2}$ $K_0=0$

C. Forssén, B. Jonson, M.V. Zhukov
NP**A673** (2008) 143



Y. Aksyutina, H. Johansson et al., PL**B666** (2008) 430

Momentum transfer small,
^{11}Li core survives collision !

→ ^{11}Li + 2n resonance picture

Evidence for existence
at 1.47(31) MeV.

Description of the three body continuum

- Reduction (CMS, E*, rot. inv)

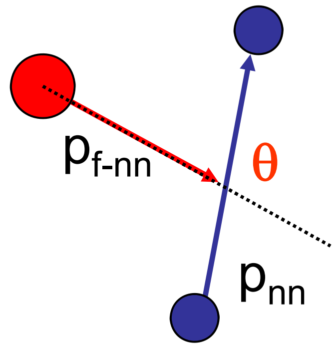
  9 variables $\rightarrow$ 2 variables **(ε, θ)**

ε is the fractional energy for a subsystem (e.g. $\varepsilon = E_{nn}/E_{nnf}$)

θ is the angle between the relative momenta (e.g. p_{nn}, $p_{f\text{-}nn}$)

- Three body correlation function (expansion in hyperspherical harm.):

$$W(\varepsilon,\theta) \propto \frac{d^2\sigma}{d\varepsilon d\theta} \propto \sum_{\alpha,\alpha'} C^{\dagger}_{\alpha'} C_{\alpha}\, \mathcal{Y}^{\dagger}_{\alpha'}(\varepsilon,\theta)\mathcal{Y}_{\alpha}(\varepsilon,\theta)$$



- Complex coefficients C depend on quantum numbers $\alpha=\{K,L,S,l_x,l_y\}$

L.V. Chulkov, H.S., I.Thompson, et al., NPA759 (2005) 23
M.Meister, L.V. Chulkov, H.S., et al., PRL91 (2003) 16504

Just Reflections of original phase space?

^{14}Be

^{13}Li

Correlations ("T")
K <= 4

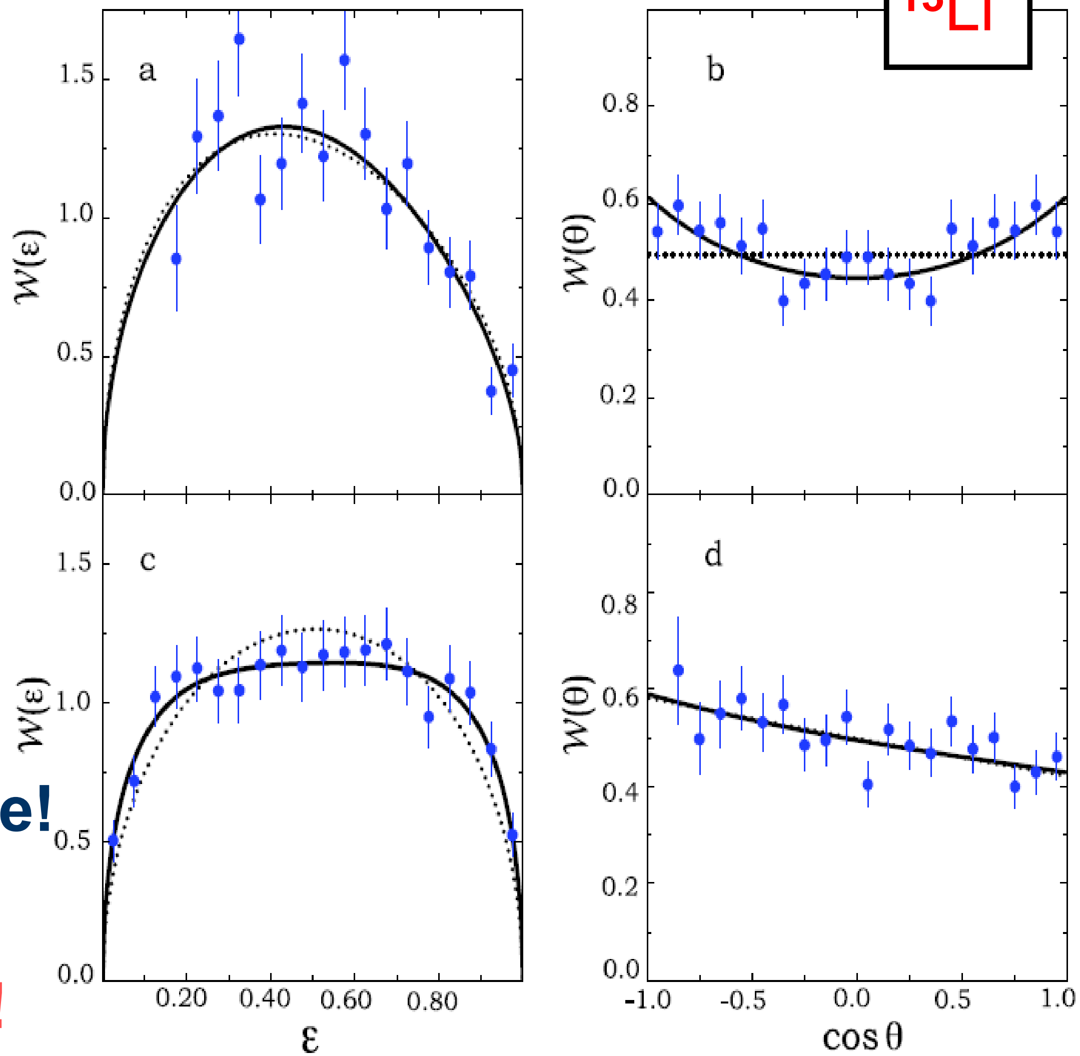
- **Strong deviations from plain phase space.**

➔ **^{13}Li existence supported**

- **Non Analogy**
^{11}Li ⇔ ^{10}He shown before!

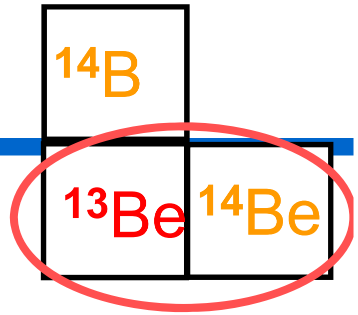
➔ **^{14}Be ⇔ ^{13}Li ?**

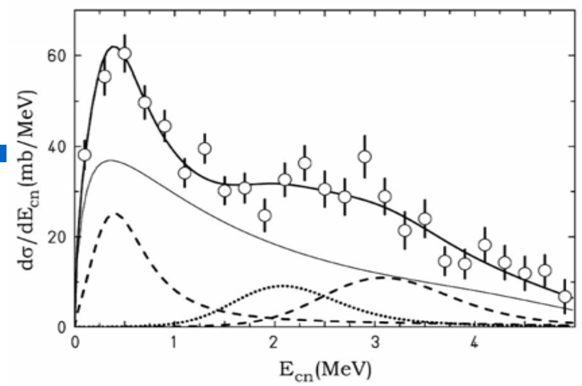
No (phenom.) ^{14}Be wf !



H.T. Johansson, Y. Aksyutina, Nucl. Phys. **A847** (2010) 66

The ^{13}Be puzzle





Virtual state dominant

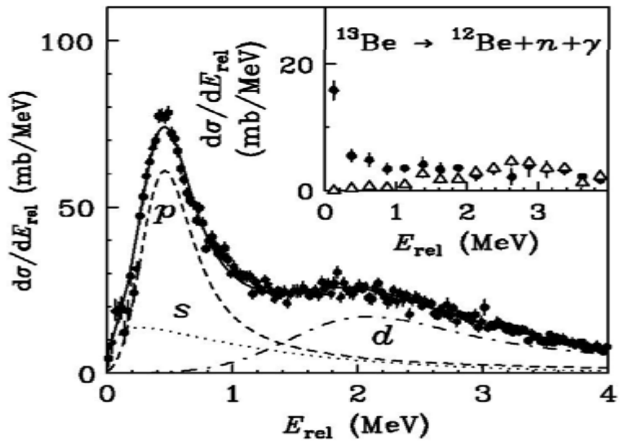
a_s= −3.2(1.0) fm (antibound state)

E_r = 0.41(8) MeV, Γ = 0.4(5) MeV

E_r = 3.04 MeV, Γ = 0.4 MeV

E_r = 2.0 MeV, Γ = 0.3 MeV

H.S. et al., Nucl.Phys. A791, 267 (2007)



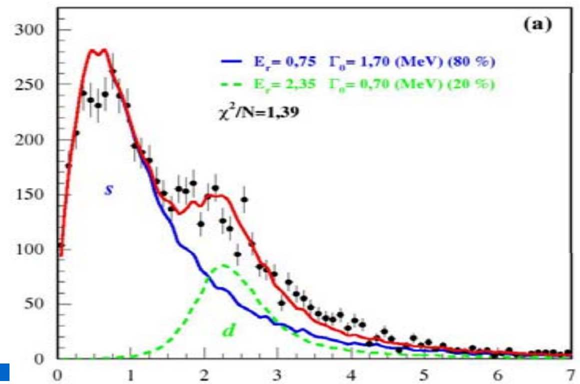
Narrow p-wave resonance

a_s= −3.4(6) fm (antibound state)

E_r = 0.51(1) MeV, Γ = 0.45(3) MeV

E_r = 2.39(5) MeV, Γ = 2.4(2) MeV

Y.Kondo et al., Phys.Lett. B 690, 245 (2010)



s-wave resonance

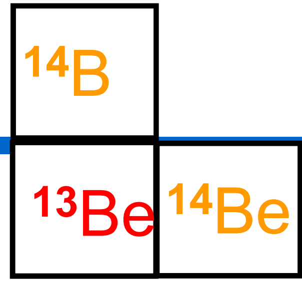
E_r=0.7(2) MeV, Γ=1.7(2) MeV

E_r=2.4(2) MeV, Γ=0.6(3) MeV

G.Randisi, PhD Thesis 2012,
see also J.L.Lecouey, Few-Body Systems 34, 21 (2004).

Recent Data:
Similar spectra
quite different
interpretations !

Questions ...



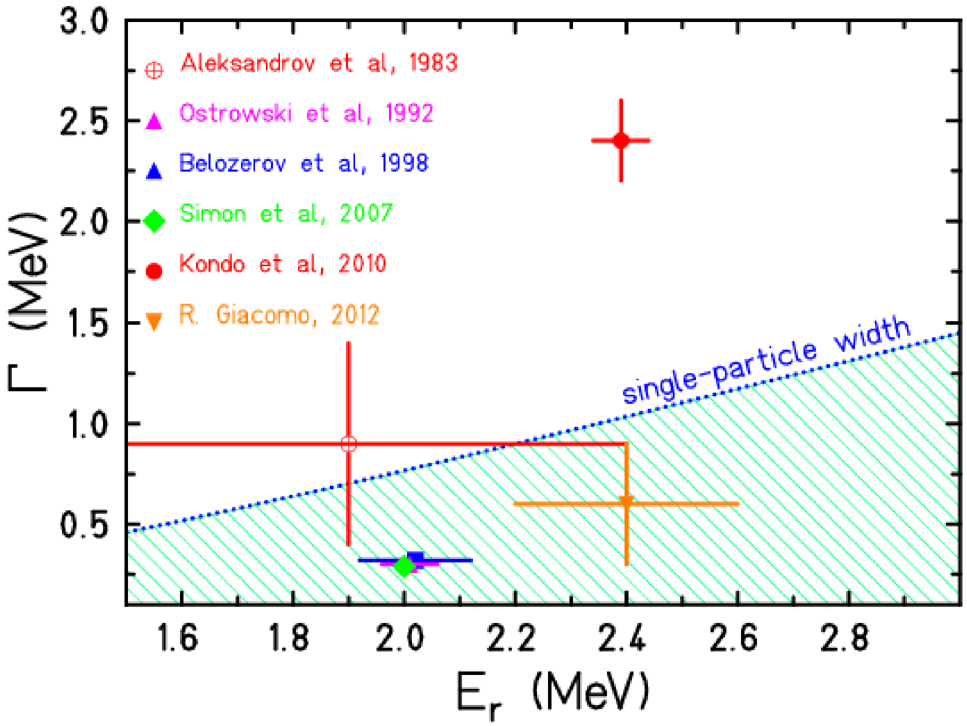
- H.S. et al., Nucl.Phys. A791, 267 (2007): Why contribution of an s-wave dominates in the relative energy spectrum when ^{12}Be+n ℓ=0 interaction is so weak?

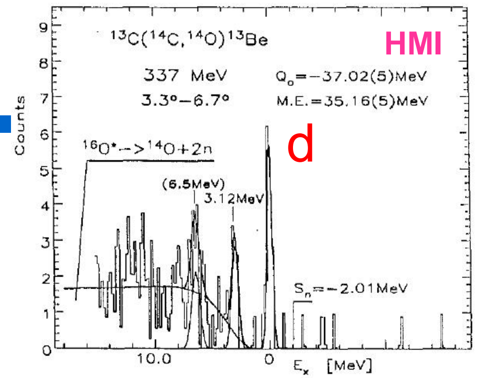
- Y.Kondo et al., Phys.Lett. B 690, 245 (2010): With the assumption of a narrow p-resonance, the low-energy region can be fitted only assuming that the d-resonance is extremely broad. The width of d-resonance is so broad ($\Gamma \approx 5/2\ \Gamma_{s.p.}$) that this fact itself can be the subject of separate publications and further investigations (see e.g. D.Overway et al , Nucl.Phys. A366, 299 (1981)).

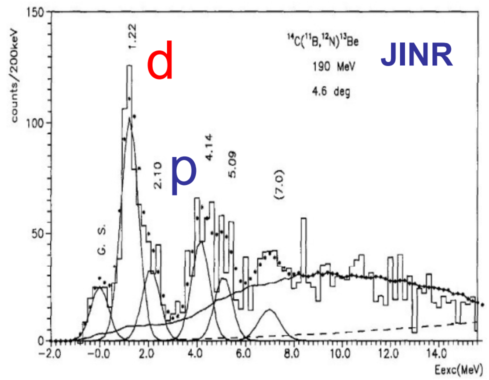
- J.L.Lecouey, Few-Body Systems 34, 21 (2004); Y.G.Randisi, PhD Thesis 2012: Why should there be a s-wave resonace with no angular momentum barrier, or how sensitive is the shape determination?
The momentum transfer in the knockout of tightly bound proton can essentially change the spectrum (see H.Esbensen et al., Phys.Rev. C57, 1366 (1998)).

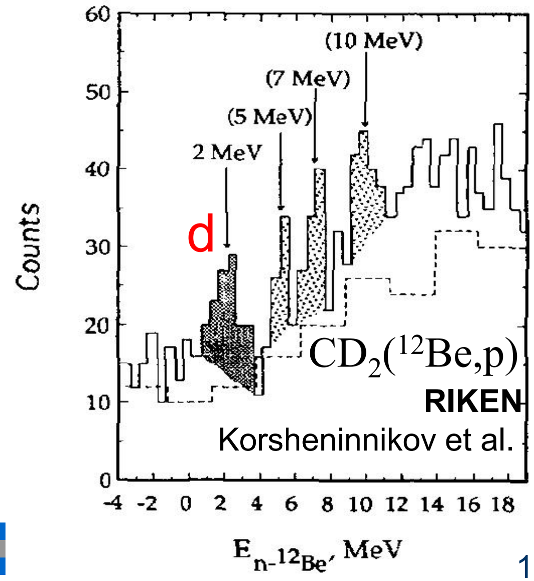
The region around 2 MeV

$5/2^+$ state(s) in ^{13}Be

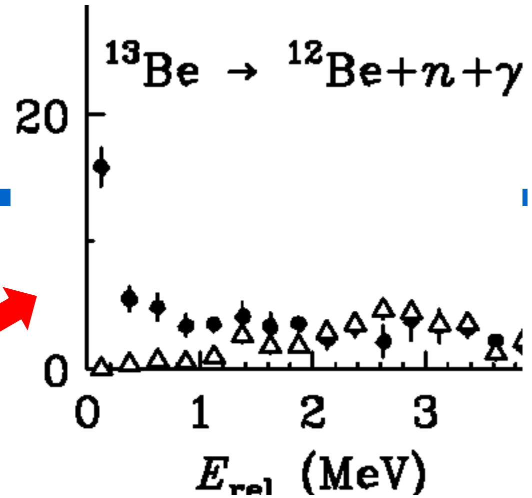




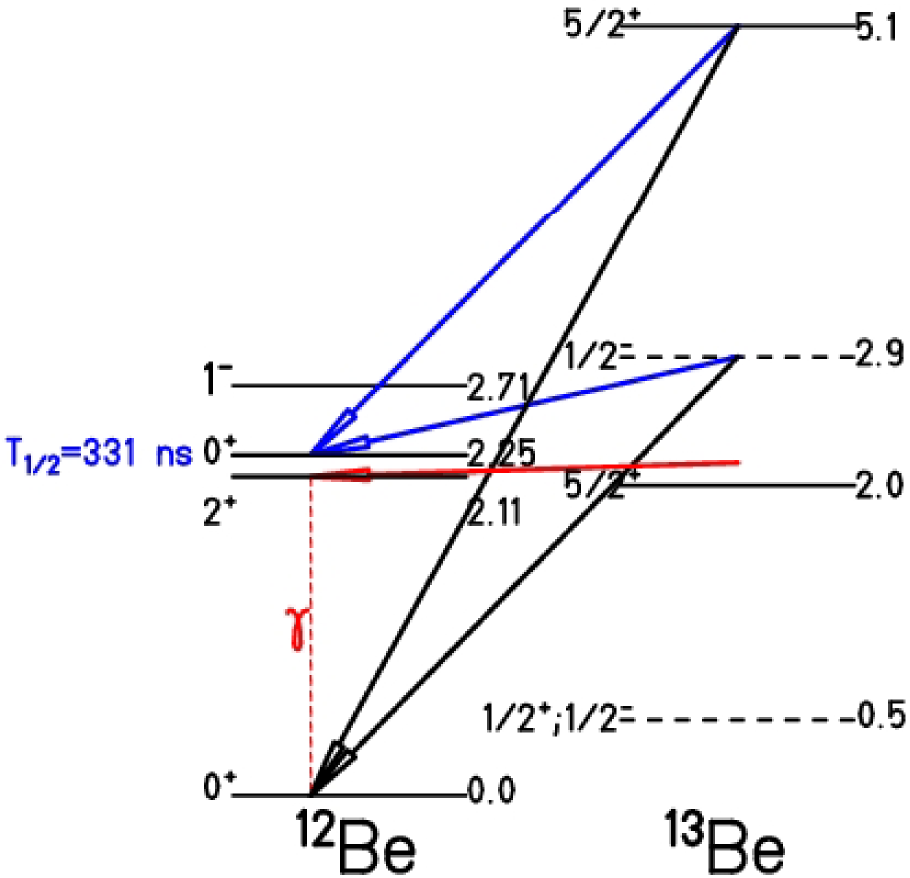


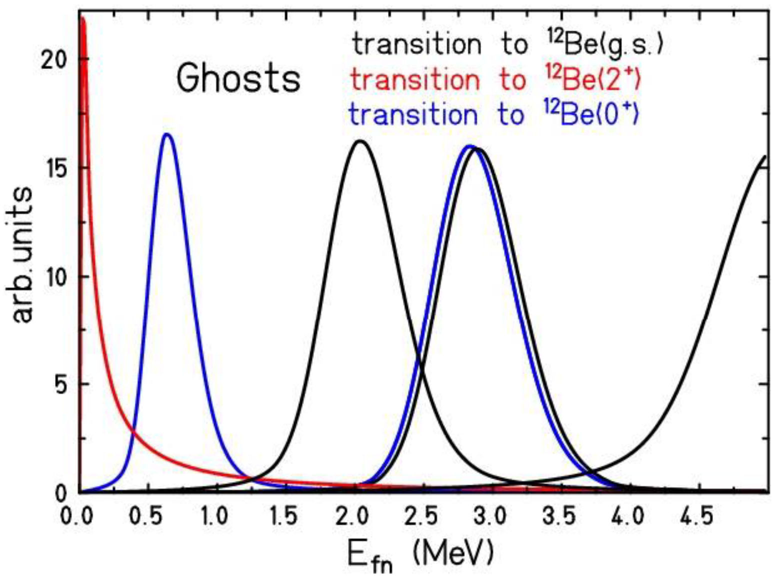


Ghosts in the ^{12}Be+n relative-energy spectrum

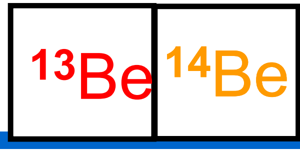


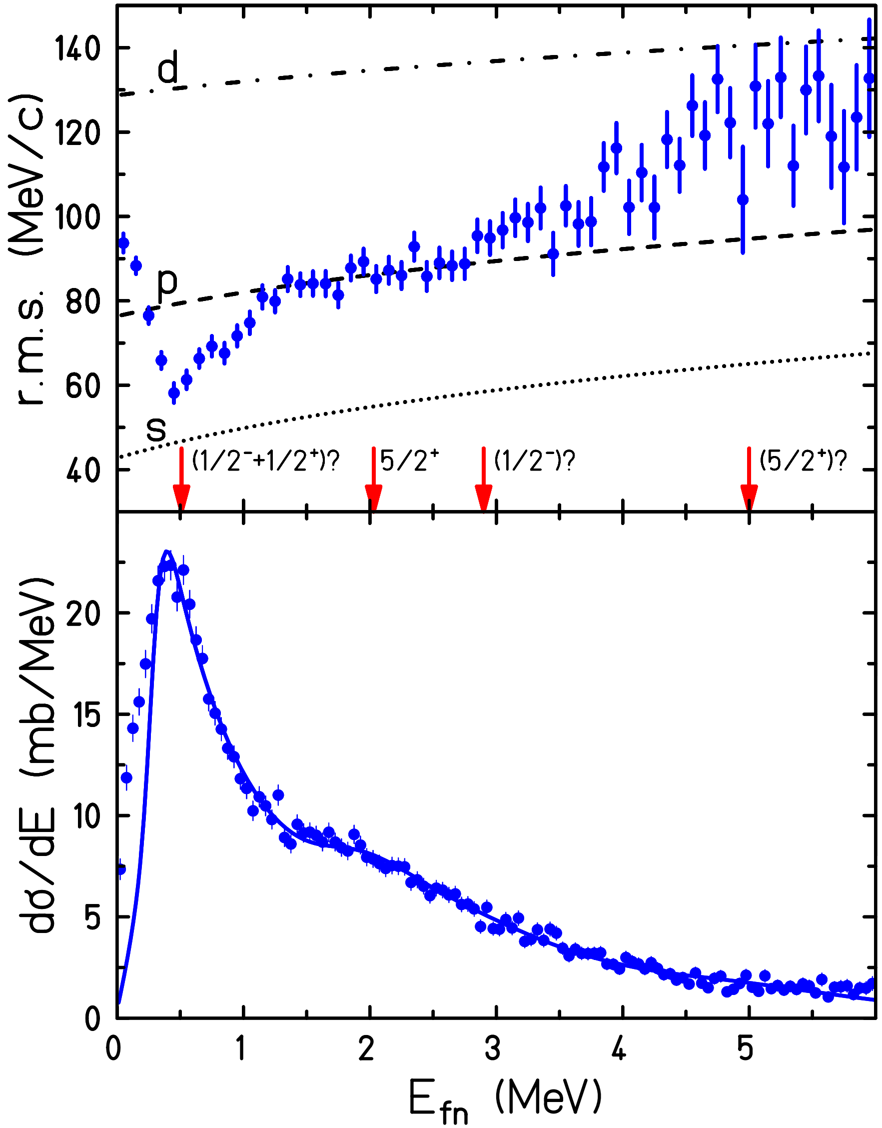
Y.Kondo et al., Phys.Lett. B 690, 245 (2010)
Coincidence with 2.7 Mev γ (triancles) and
2.1 MeV γ (circles)



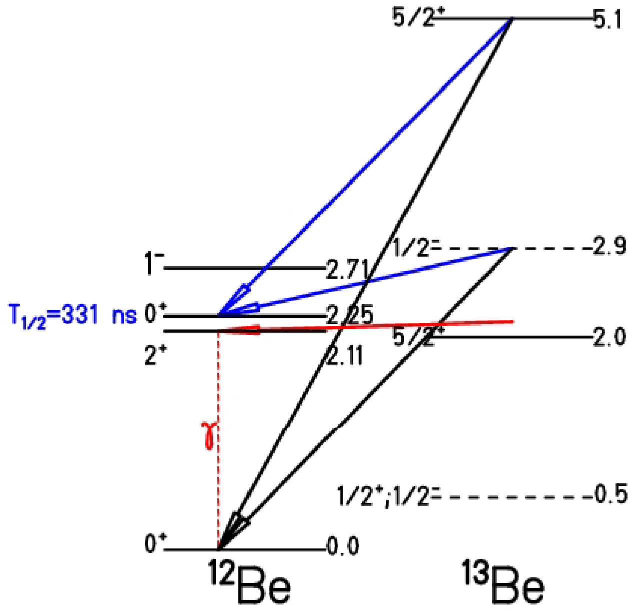


Momentum profile





Y. Aksyutina et al., submitted



- d ghost at threshold
- s strength above
- then p,d states & ghosts

Experimental challenge: Multineutron detection

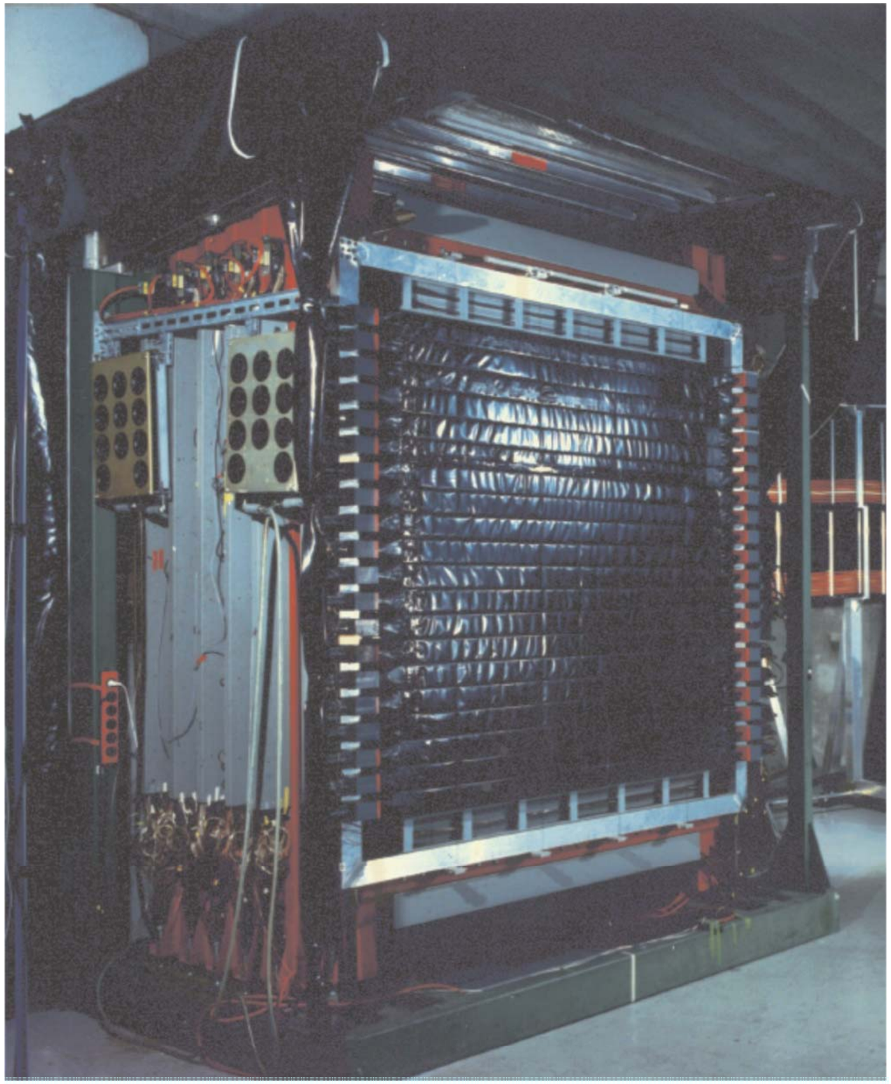
coincident two/four neutron + charged fragment detection

- two neutron detection efficiency
- two neutron reconstruction efficieny
- detector response

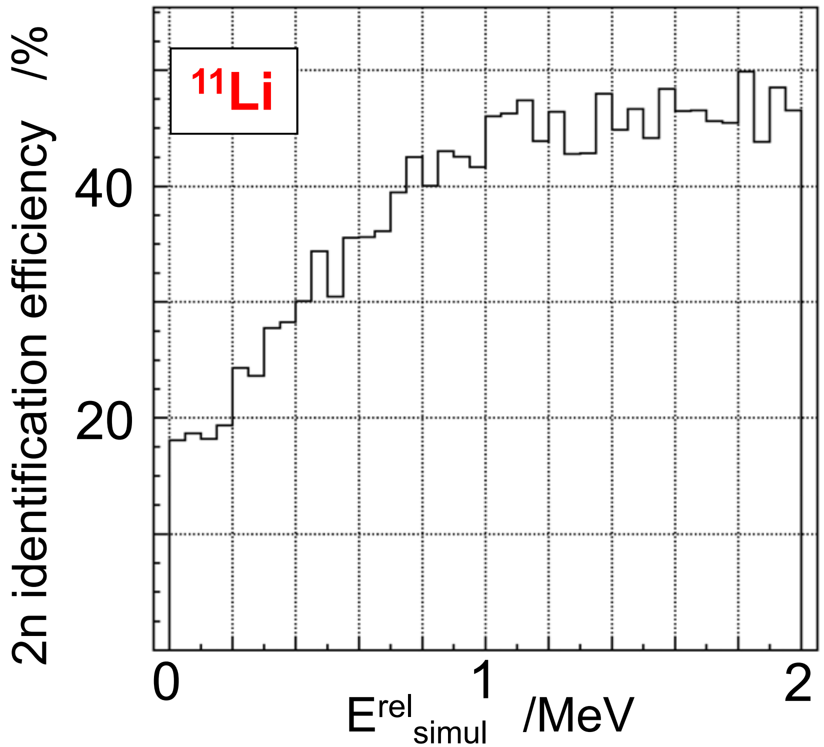
@ low relative energy !

three/five body correlations

LAND 2n identification efficiency at low energy

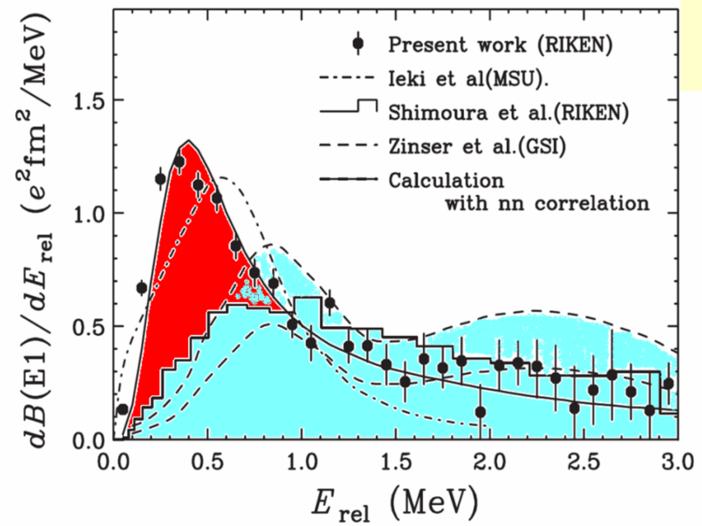


Nucl. Instr. Meth. A314 (1992) 136

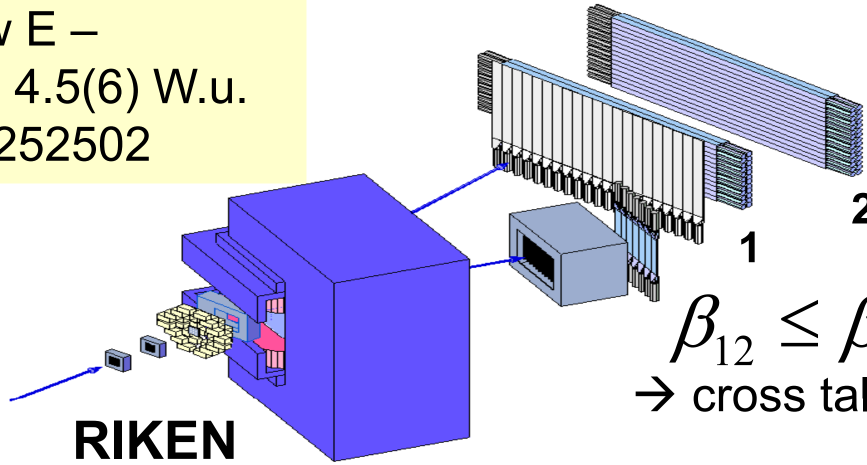


- (high) 2n detection efficiency (98%)
- tracking algorithm
  → 2n identification efficiency
- identify 2n events (~ 20 %)
  even at zero relative energy

Experimental evidences…



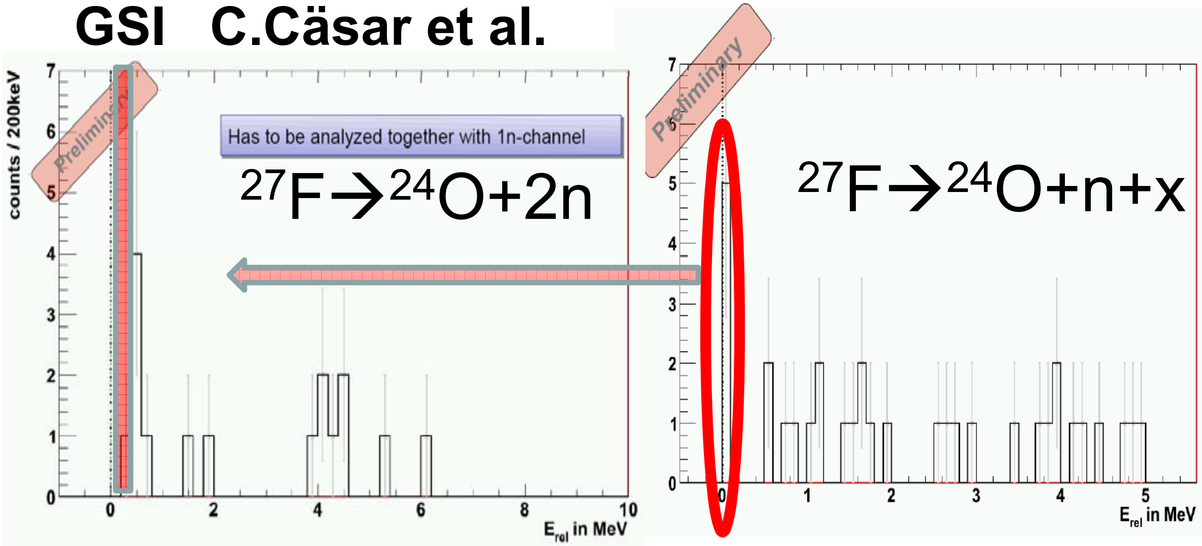
„Strongest low E – E1 transition" 4.5(6) W.u. PRL**96**(2006)252502

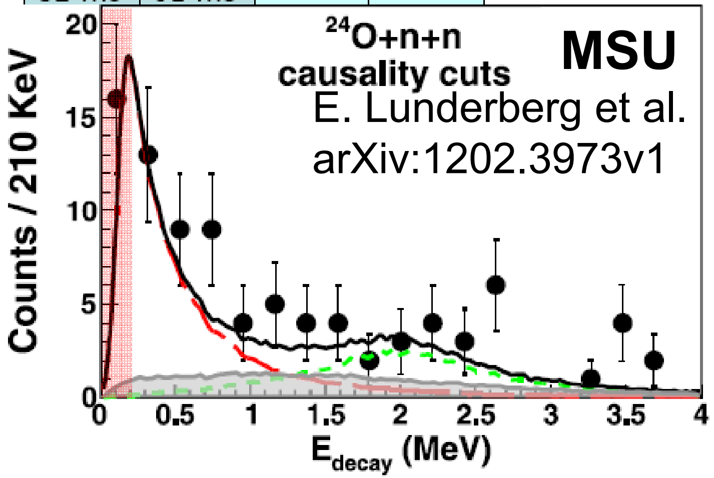


$\beta_{12} \leq \beta_1$
→ cross talk

^{24}F 0.34 s	^{25}F 50 ms	^{26}F 10.2 ms	^{27}F 4.9 ms	^{28}F unbound	^{29}F 2.6 ms
^{23}O 82 ms	^{24}O 61 ms	^{25}O unbound	^{26}O unbound		

GSI C.Cäsar et al.

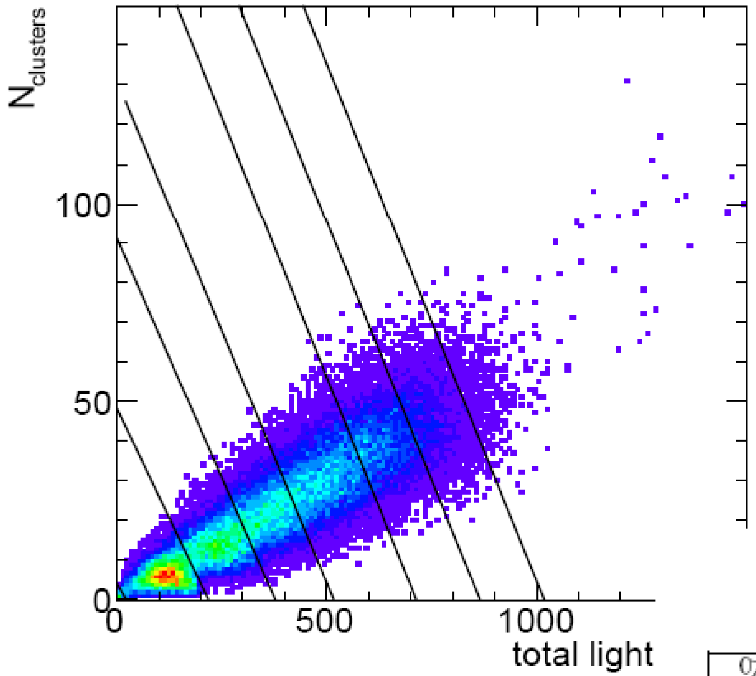


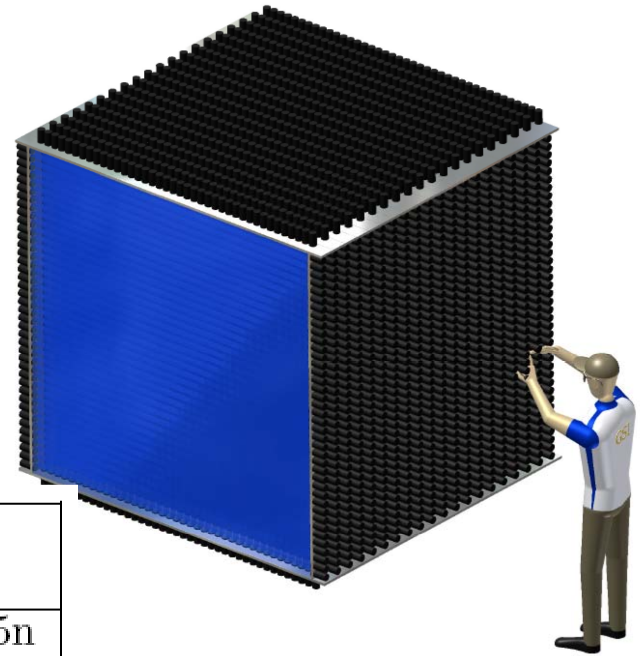


Going for a different detector concept → R³B@FAIR

Can a NeuLAND detector based on scintillators fulfil the design criteria?

➔ Yes, NeuLAND TDR submitted Nov2011





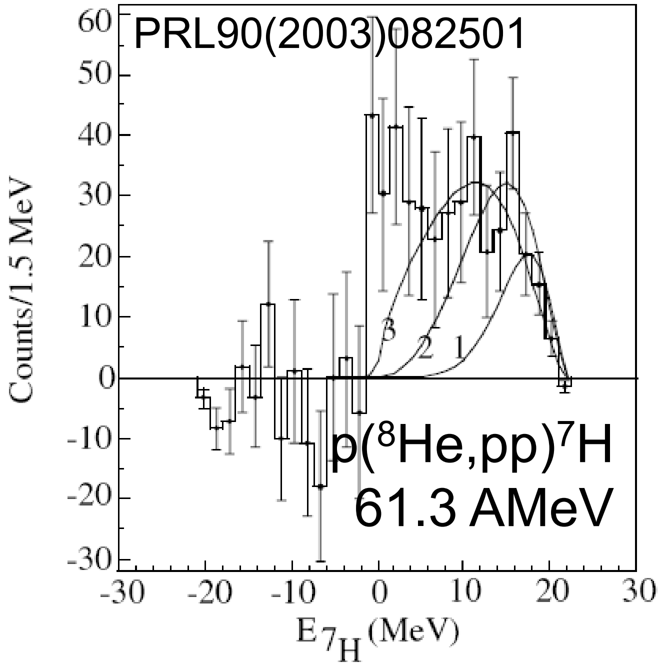
	%	1000 MeV generated 1n	2n	3n	4n	5n
detected	1n	**89**	12	1	0	0
	2n	7	**78**	23	3	0
	3n	0	8	**63**	26	5
	4n	0	0	12	**63**	40
	5n	0	0	0	7	**46**
	6n	0	0	0	0	8

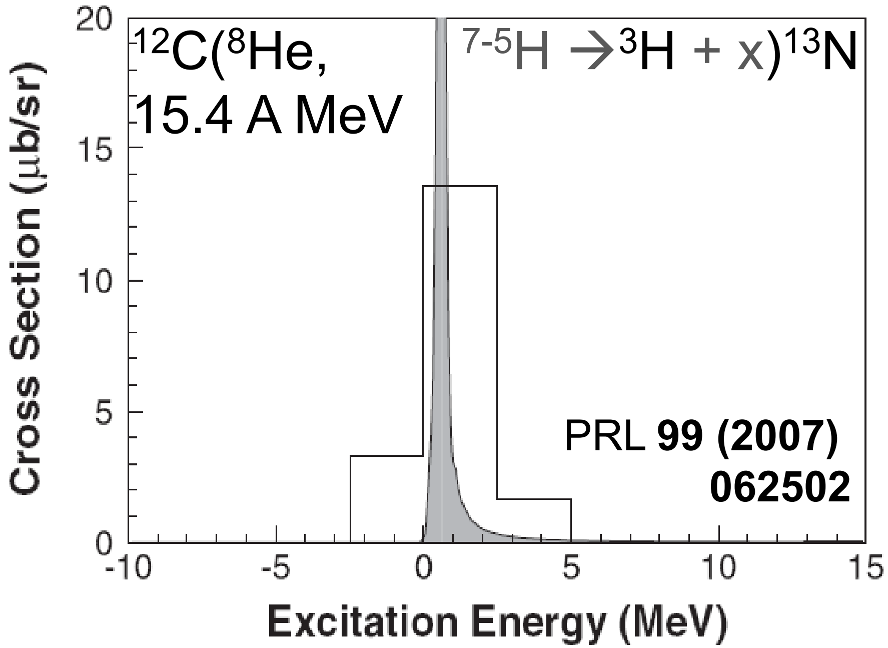
Previously **< 50%**

Previously **<5%** !

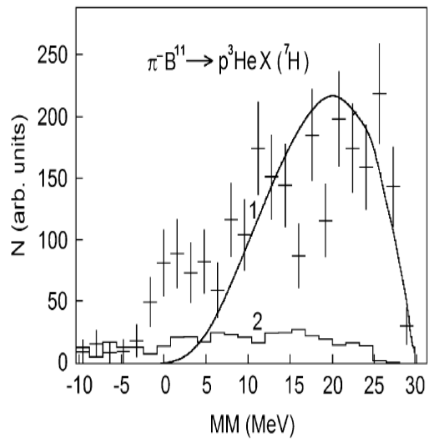
30 double planes
2 x 50 paddles each
5 x 5 x 250 cm³
RP408 / R8619ASSY
Tacquila readout

Beyond the dripline: ^{7}H (just) missing mass spectra

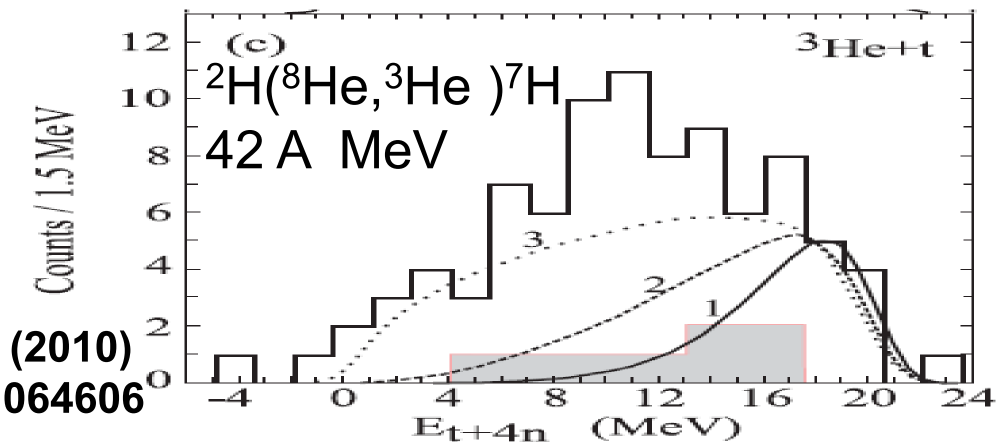




EPJA 32
(2007) 261



PRC81 **(2010)**
064606



Incredients for the ^{7}H case

t + n + n + n + n

PHYSICAL REVIEW C 77, 054317 (2008)

Strong dineutron correlation in ^{8}He and ^{18}C

K. Hagino,[1] N. Takahashi,[1] and H. Sagawa[2]

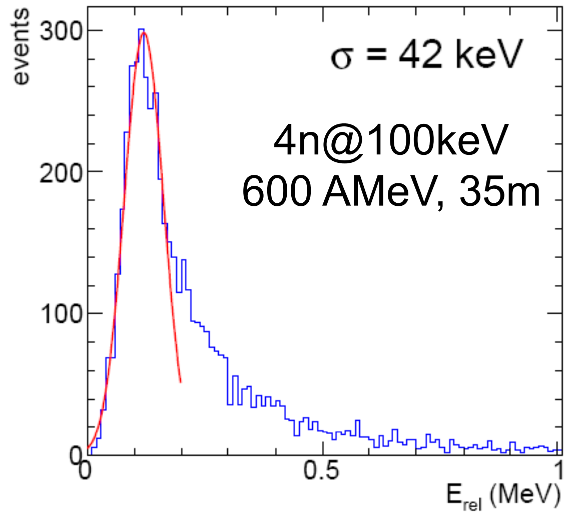
Core +4n (HFB)

PHYSICAL REVIEW C **80**, 021304(R) (2009)

Di-neutron correlations in ^{7}H

S. Aoyama[1] and N. Itagaki[2]

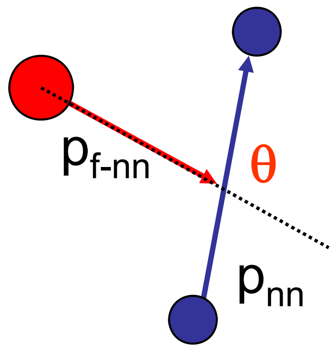
Core +4n
AMD selected snapshots



NeuLAND Simul.

t + 2n + 2n

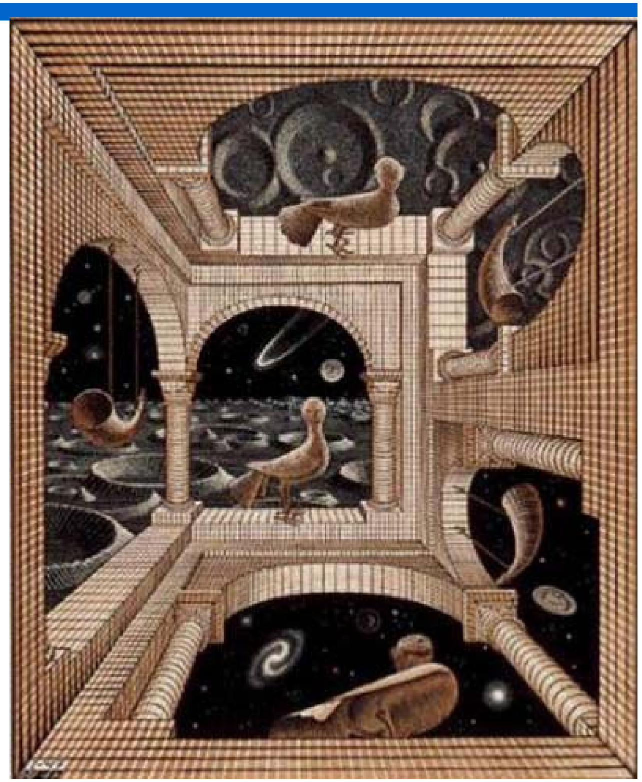
^{11}Li - α → ^{7}H + 2n + 2n
^{8}He – p → ^{7}H + 2n + 2n

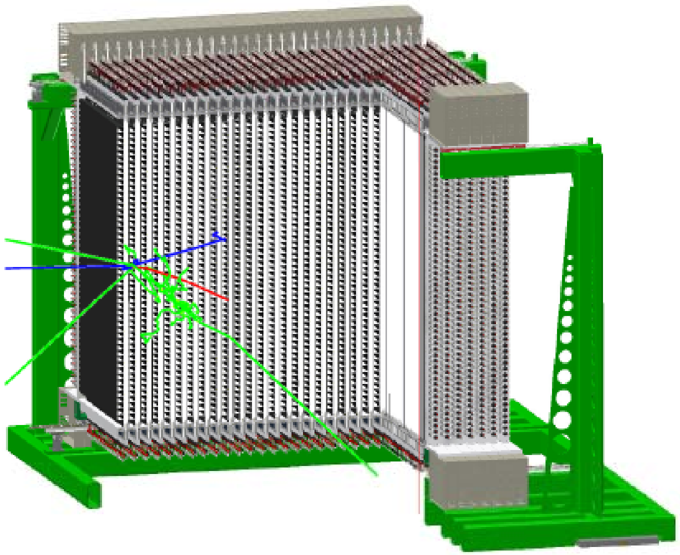


3 bdy corr.

Summary

- Extreme nuclear matter states
  cleanly produced and analysed
- Largest neutron/proton asymmetries
- ^{13,12}Li related to ^{14,13}Be properties
- LAND multi-neutron response
  low energy part of Erel for f + n + n
  studied and characterized
  (^{11}Li, ^{26}O)





- Neuland TDR (R³B@FAIR)
  fully active detector
  consistent simulation

➔ f + n + n + n + n (e.g. ^{7}H) in reach

The NeuLAND working group within the R³B collaboration

Convener: Konstanze Boretzky, GSI Darmstadt, Germany
Deputy: Ushasi Datta Pramanik, SINP Kolkata, India

GSI Darmstadt: D. Bertini, K. Boretzky, J. Hehner, M. Heil, G. Ickert, Y. Leifels, D. Rossi, H. Simon
HZDR Dresden-Rossendorf: D. Bemmerer, T. Cowan, Z. Elekes, M. Kempe, M. Sobiella, D. Stach, A. Wagner, J. Wüstenfeld, D. Yakorev
TU Darmstadt: T. Aumann, C. Caesar, D. Gonzalez Diaz, A. Ignatov, D. Kresan, H. Scheit
TU Dresden: T. Cowan, M. R oder, K. Zuber
U Cologne: J. Endres, A. Hennig, V. Maroussov, A. Zilges
U Frankfurt: R. Reifarth, M. Volknandt
SINP Kolkata: B. Agrawal, P. Basu, P. Bhattacharya, S. Bhattacharya, S. Chakraborty, S. Chatterjee, U. Datta Pramanik, P. Kumar Das, J. Panja, A. Rahaman, J. Ray, T. Sinha
LIP Coimbra: A. Blanco, P. Fonte, L. Lopez
U Lisbon: D. Galaviz Redondo, J. Machado, P. Teubig
ISS Bucharest: M. Cherciu, M. Ciobanu, M. Haiduc, M. Potlog, E. Stan
Kurchatov Institute Moscow: L. Chulkov
PNPI St. Petersburg: G.D. Alkhazov, V.A. Andreev, A.A. Fetisov, V.L. Golovtsov, E.A. Ivanov, A.G. Krivshich, L.N. Uvarov, V.V. Vikhrov, S.S. Volkov, A.A. Zhdanov
Chalmers Univ. of Technology: A. Heinz

The Halo Collaboration

Y. Aksyutina, T. Aumann, H. Álvarez-Pol, T. LeBleis, E. Benjamim, J. Benlliure, K. Boretzky, M.J.G. Borge, C. Caesar, M.Caamaño, E. Casarejos, L.V. Chulkov, D. Cortina-Gil, K. Epinger, Th. W. Elze, H. Emling, C. Forssén, H. Geissel, R. Gernhäuser, M. Hellström, J. Holeczek, K.L. Jones, H. Johansson, B. Jonson, J.V. Kratz, R. Krücken, R. Kulessa, C.Langer, M. Lantz, Y. Leifels, A. Lindahl, K. Mahata, M. Meister, P. Maierbeck, K. Markenroth, G. Münzenberg, T. Nilsson, C. Nociforo, G. Nyman, R. Palit, M. Pantea, S. Paschalis, D.Pérez, M. Pfützner, V. Pribora, A. Prochazka, R. Reifarth, A. Richter, K. Riisager, C. Rodríguez, C. Scheidenberger, G. Schrieder, H. Simon, J. Stroth, K. Sümmerer, O. Tengblad, H. Weick, and M.V. Zhukov.

**GSI, Darmstadt, Germany; Instito Estructura de la Materia, Madrid, Spain
Kurchatov Institute, Moscow, Russia; Johann-Wolfgang- Goethe-Univ., Frankfurt, Germany;
Chalmers Tekniska Högskola / Göteborgs Universitet, Göteborg, Sweden;
Johannes-Gutenberg-Universität, Mainz, Germany;
Universytet Jagiellonski, Kraków, Poland;
University Santiago de Compostela, Spain;
Technische Universität, Darmstadt, Germany; Technische Universität, München, Germany;
CERN, Genève, Switzerland; Aarhus Universitet, Aarhus, Denmark**

Open Quantum Systems

ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY
Institutional Member of the ESF Expert Committee NuPECC

Base properties of clustered systems and halo nuclei

Halo effective field theory

Cluster models

Gamow / continuum shell model

Nuclear systems close to breakup threshold:

- Influenced by correlations and couplings to the continuum
- Clusterization; dilute matter densities
- Melting of shell structure
- Ground-states embedded in the continuum

...open quantum systems

Interface between clustering and continuum in structure and reactions

Ab initio reaction theory

Bound-state techniques for scattering properties

Director of the ECT*: Professor Achim Richter (*ECT**)

The ECT* is sponsored by the "Fondazione Bruno Kessler" in collaboration with the "Assessorato alla Cultura" (Provincia Autonoma di Trento), funding agencies of EU Member and Associated States and has the support of the Department of Physics of the University of Trento.

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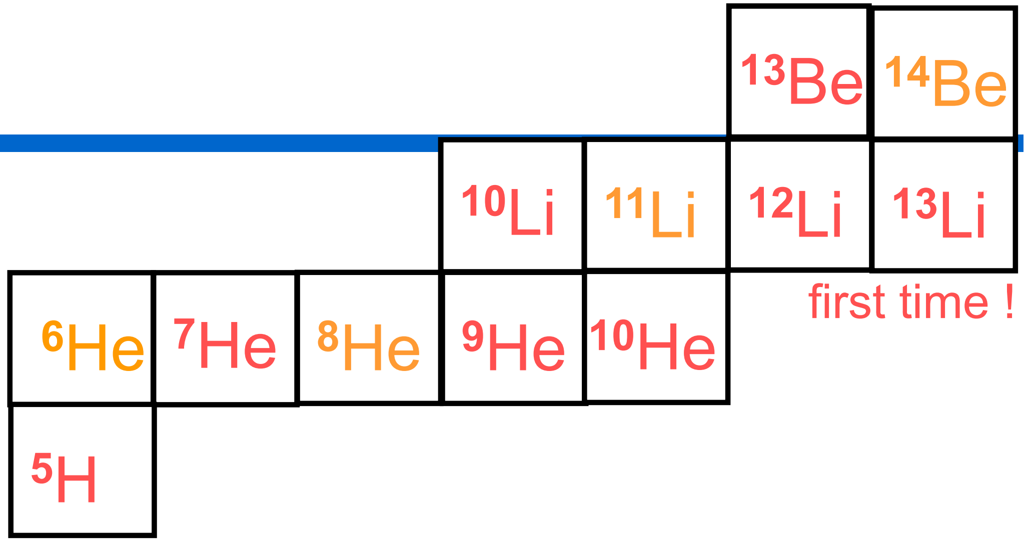
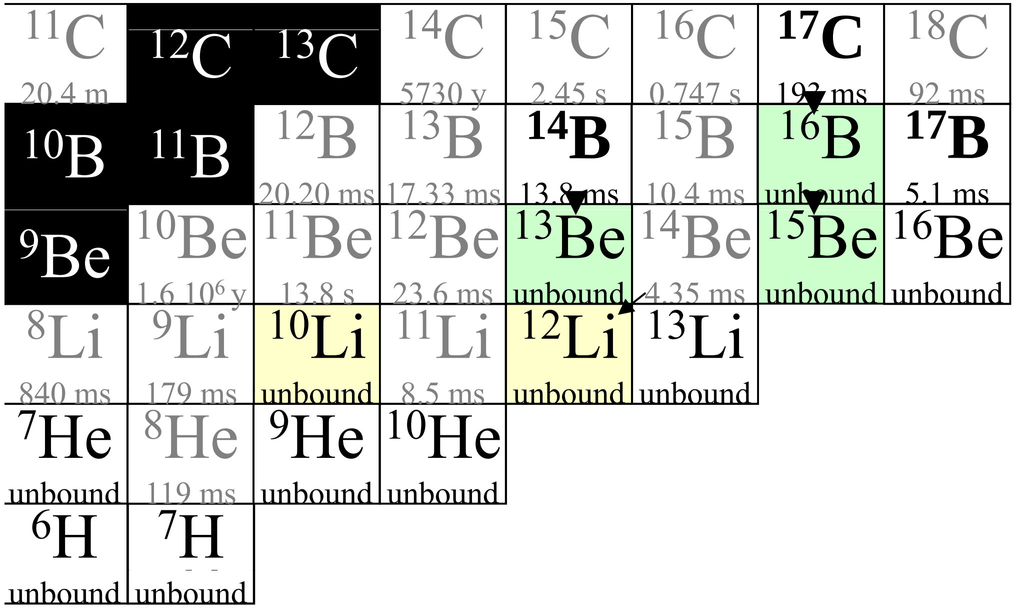
Tel.: (+39-0461) 314-721 Fax: (+39-0461) 935007, E-mail: ***ect@ect.it*** *or visit* ***http://www.ect.it***

Conclusion/Outlook

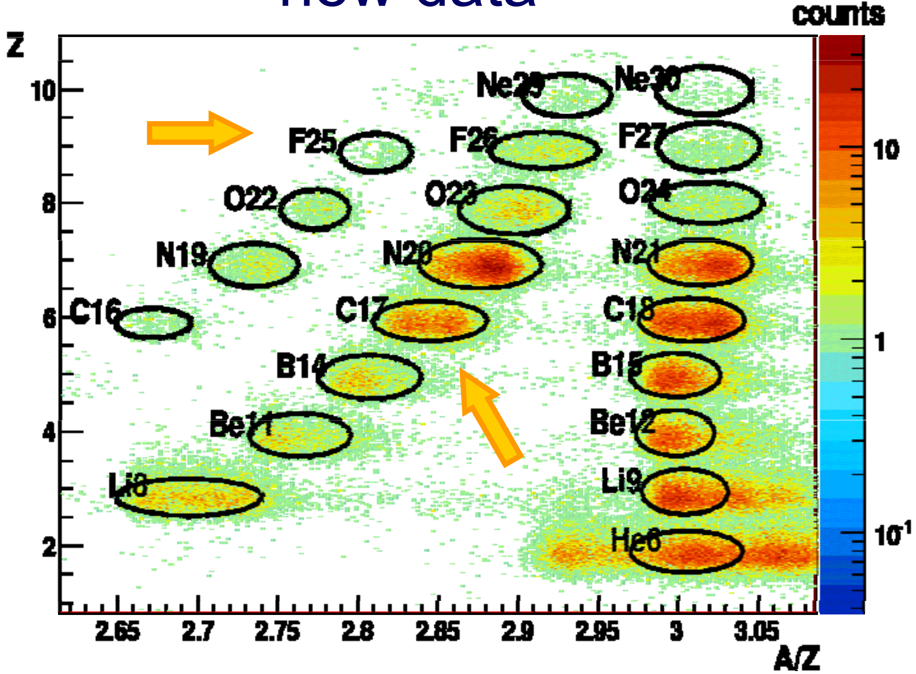


- Comprehensive study of exotic unbound systems with extreme A/Z

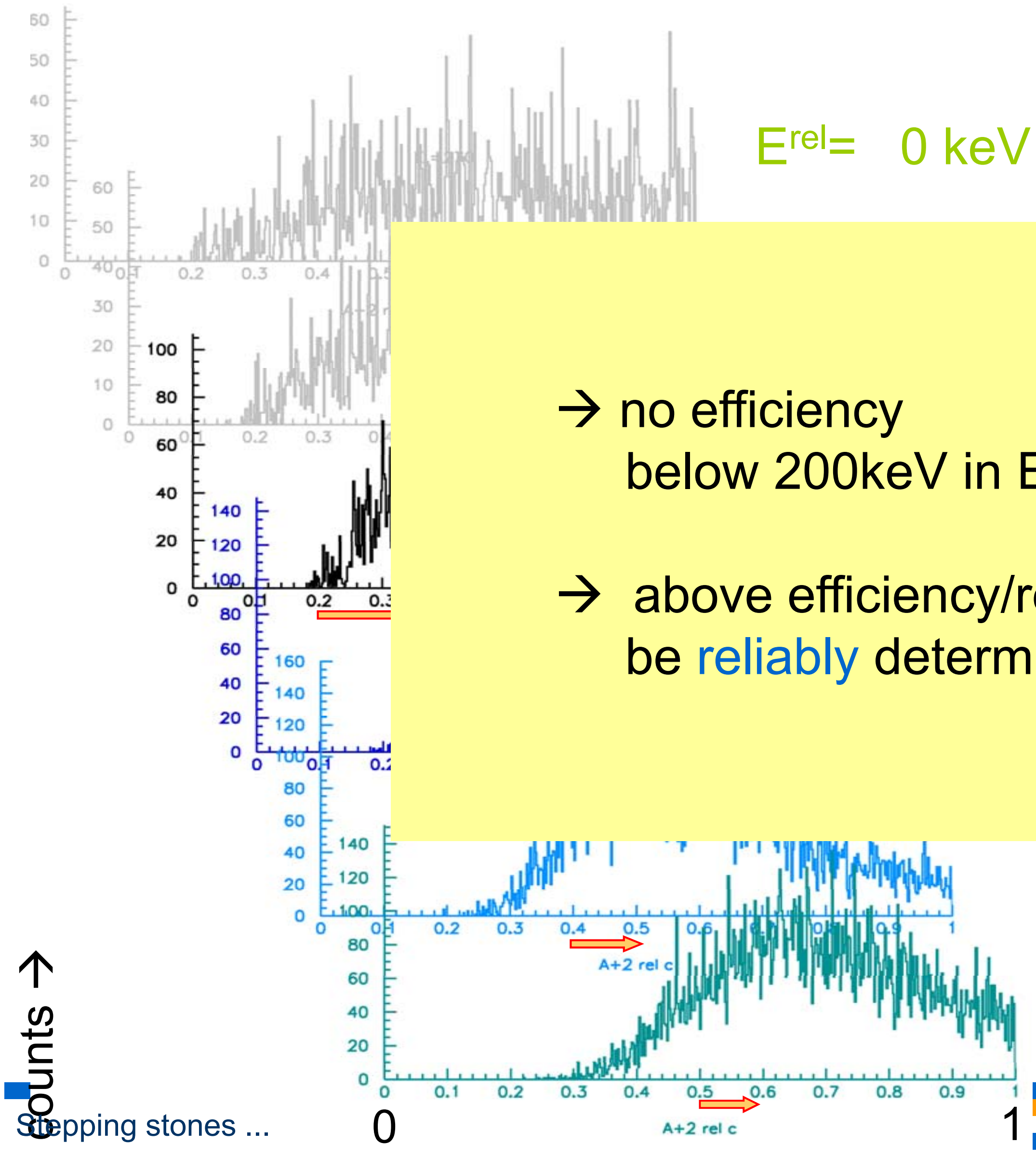
- Structure information unveiled

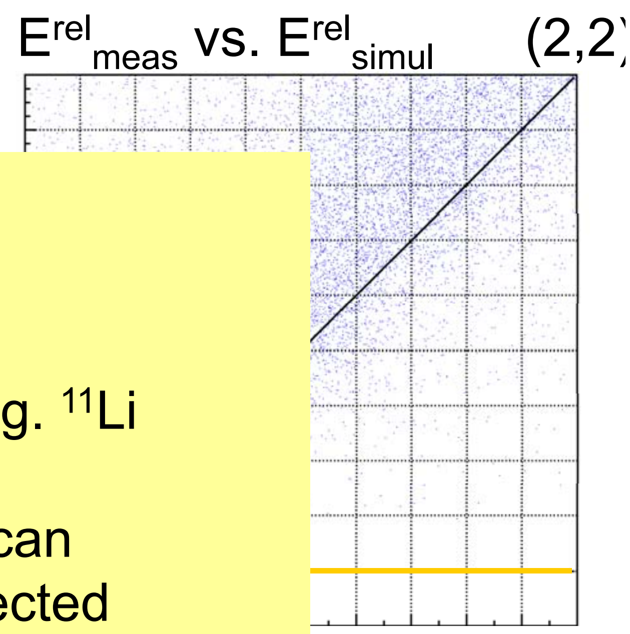


new data



LAND response at low energy





→ no efficiency below 200keV in Erel for e.g. ^{11}Li

→ above efficiency/response can be reliably determined/corrected

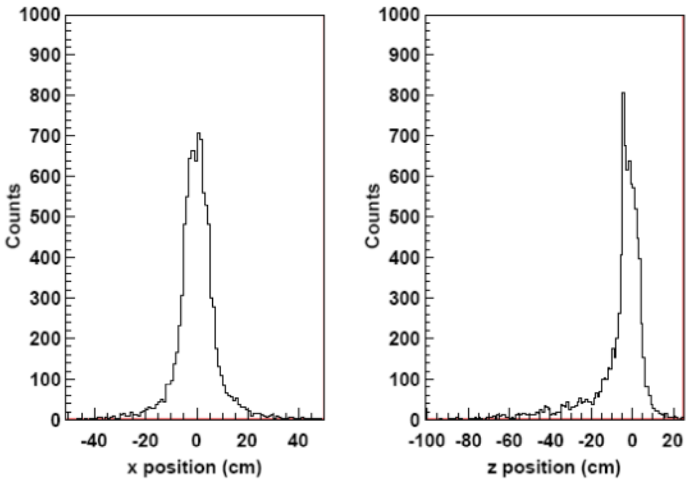
^{11}Li

Consequences for a NewLAND detector

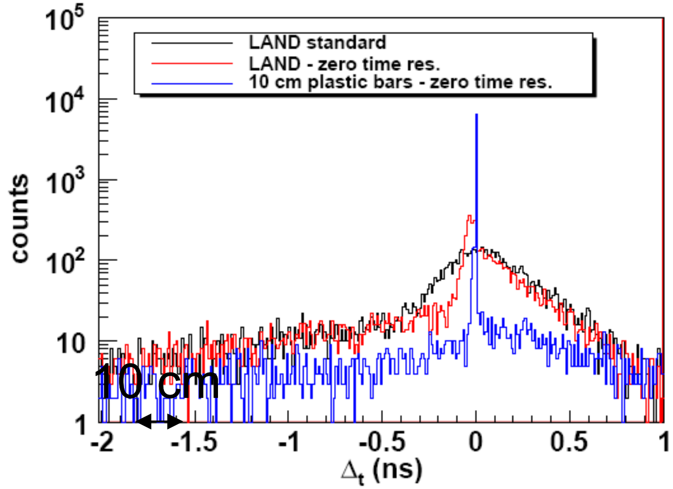
http://fairroot.gsi.de

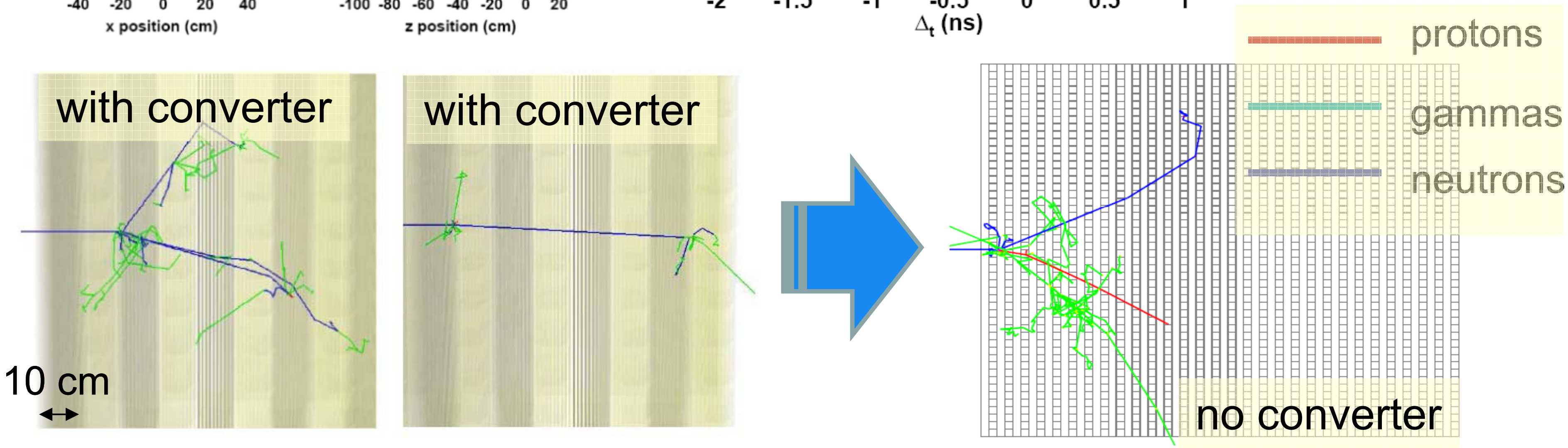
D. Bertini,
K. Boretzky,
M. Heil,
D. Kresan

Land position resolution



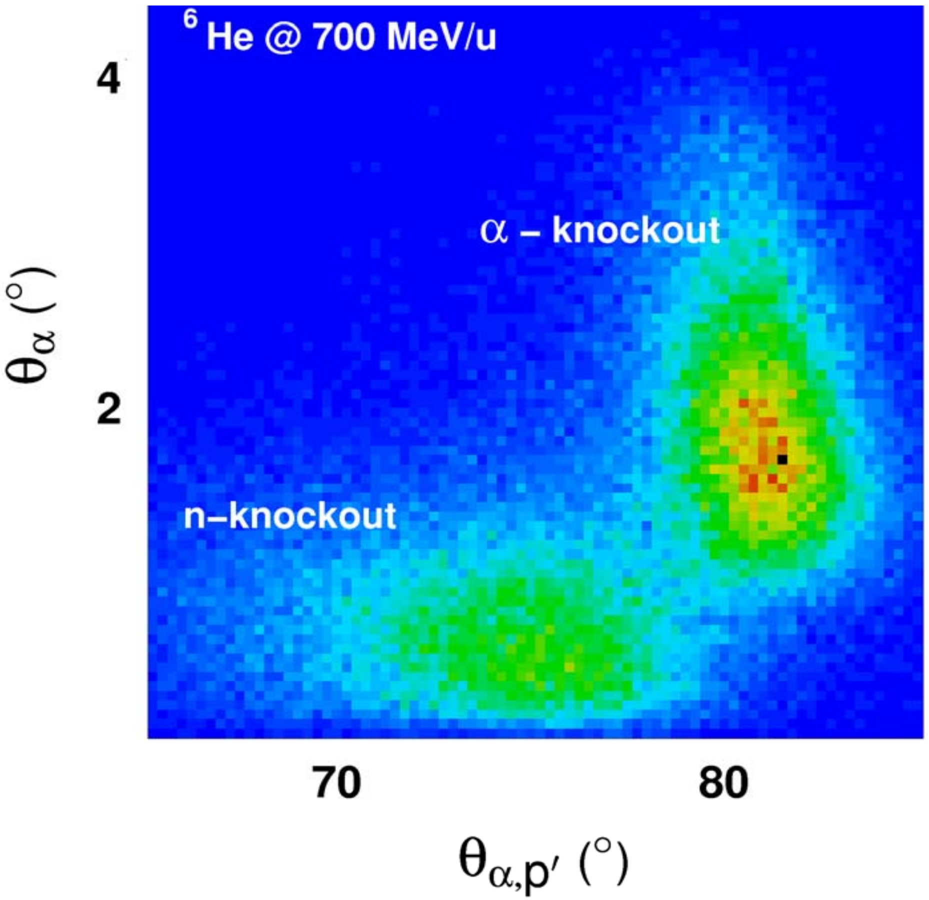
intrinsic time resolution with and without passive converter



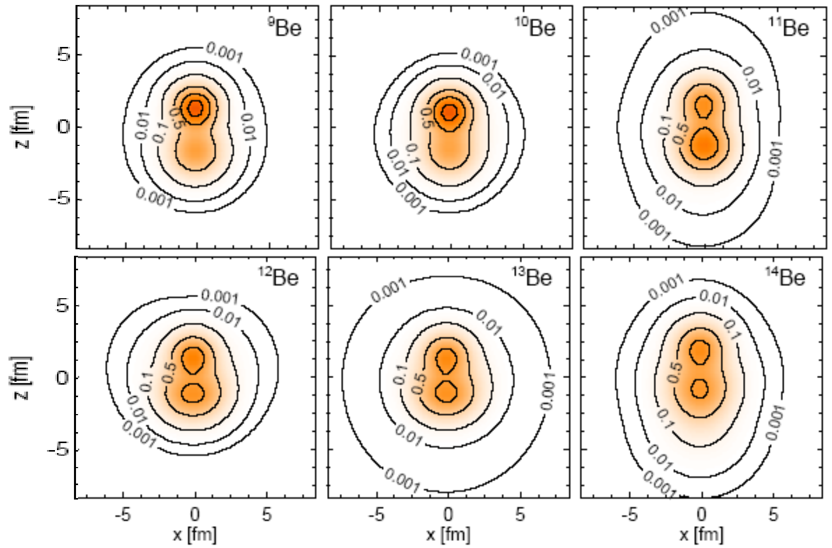


Clean handle on reaction mechanism:
→ Si tracker & Crystal ball or CALIFA

L.V. Chulkov et al., Nucl. Phys. **A759**(2005)43



T. Neff et al., Nucl. Phys. **A752**(2005)321c



liquid hydrogen or CH_2 target
& recoil proton detection

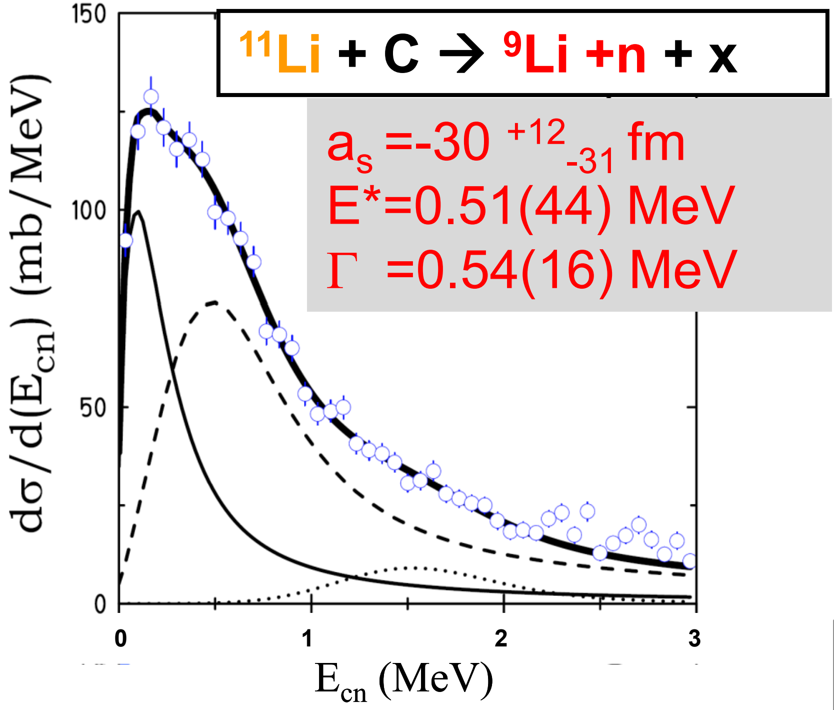
Direct observation of kinematical correlations →

(i) (Cluster) spectroscopic factors
(p,2p),(p,pn),(p,px) inv. kinematics

(ii) clean production of **^{4}H, ^{7}H,…**
via **α** knockout !

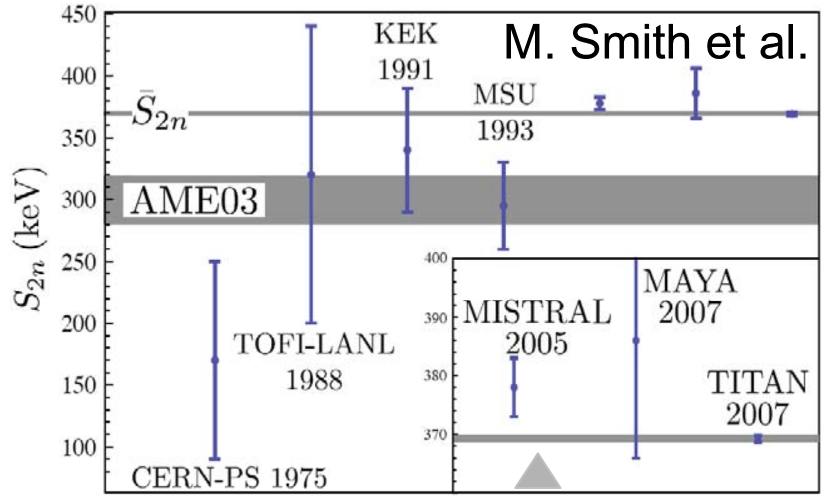
The structure of ^{11}Li via ^{10}Li

^{10}Li	^{11}Li



H.S. et al.
Phys. Rev. Lett. **83** (1999) 496
Nucl. Phys. **A 791** (2007) 267

→Confirmed eg @ GANIL
^{11}Be, ^{14,15}B → ^{9}Li+n
H. Al Falou et al. Niigata 2010



PRL **101,** 202501 (2008) Nucl.Phys.**A826,** 1 (2009)

Correlation data, matter radii, B(E1), cross sections

binding energy 369.15(65) keV
charge radius 2.467(37) fm
R. Sanchez et al., PRL**96** (2006) 033002
quadrupole moment 33.3 (5) mb
R. Neugart et al., PRL**101**(2008)132502

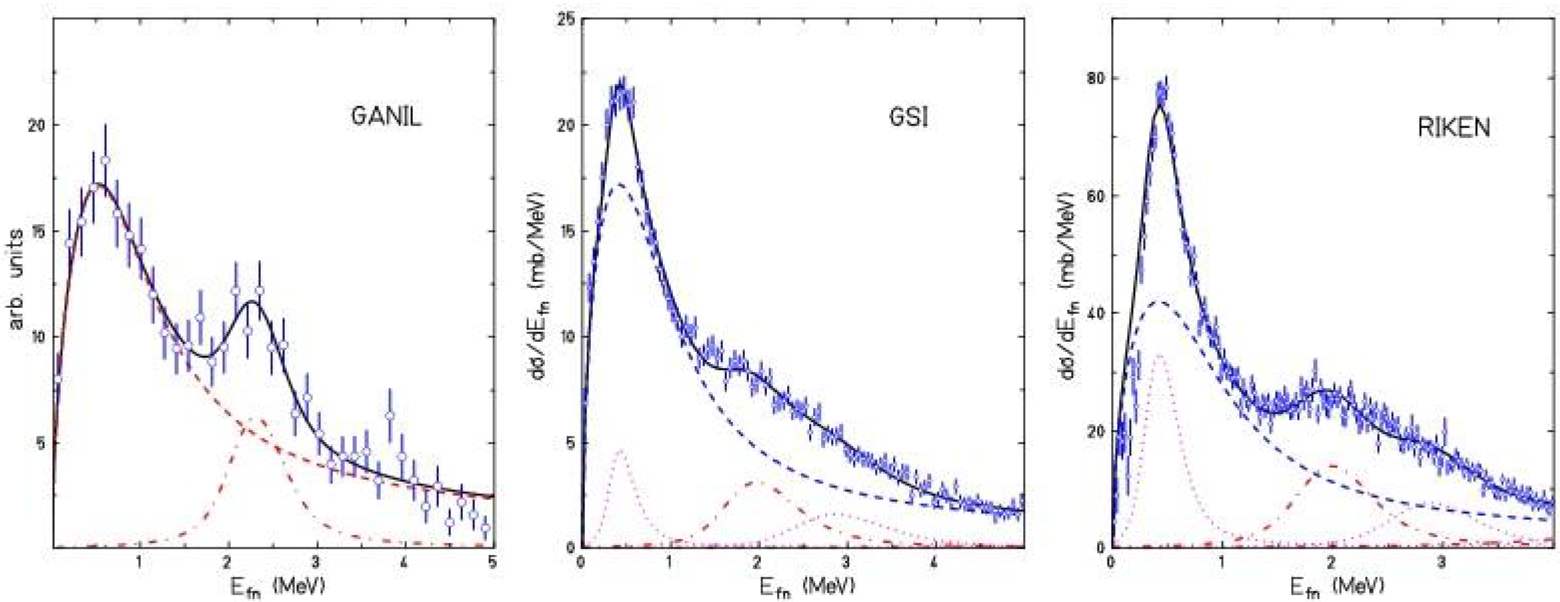
Phenomenological wave function
N.B. Schulgina, B. Jonson, M.V.Zhukov
Nucl. Phys. **A825**(2009)175

(s1/2)²: 37%
(p1/2)²: 47%
(p3/2)²: 9%

Consistent description of all data sets

^{14}B
^{13}Be ^{14}Be

R-matrix parameterisation for the phase shift (ℓ=0).

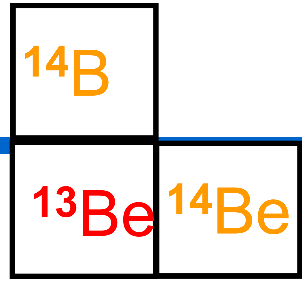


JINR

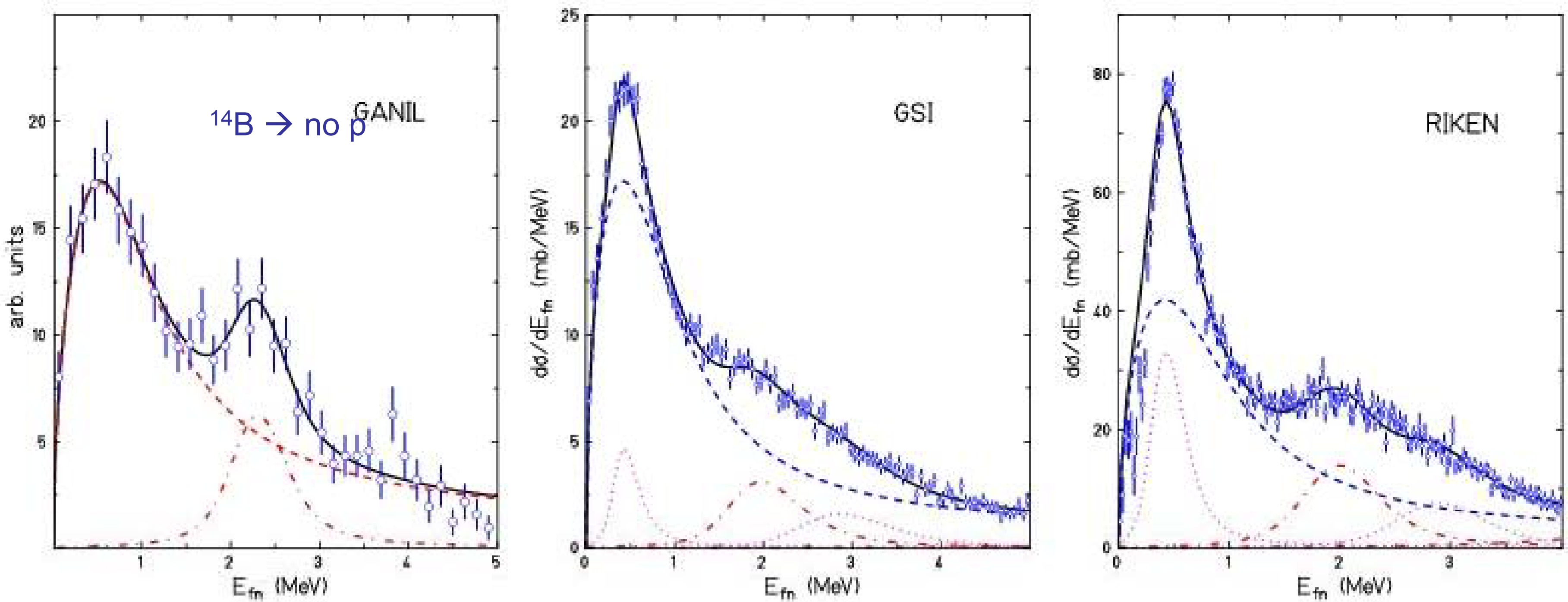
Background phase shift dl= - atan Fl/Gl = - rho taken into account -> Esbensen k for initial

L.V. Chulkov

Consistent description of all data sets



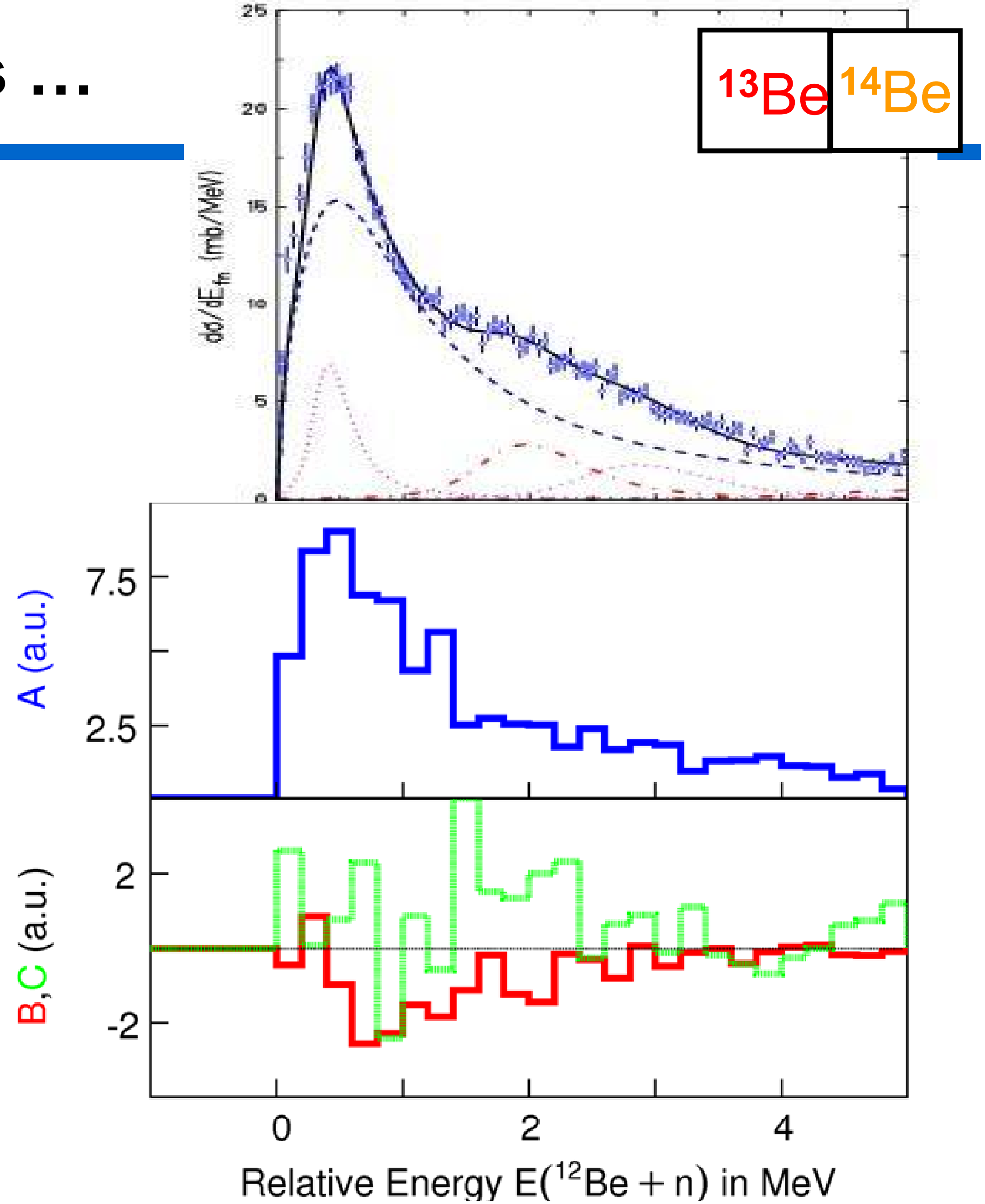
- s wave fit
- p,d fixed from experiment



Bertsch, Hencken, Esbensen, PR**C57**(1998)1366

L.V. Chulkov

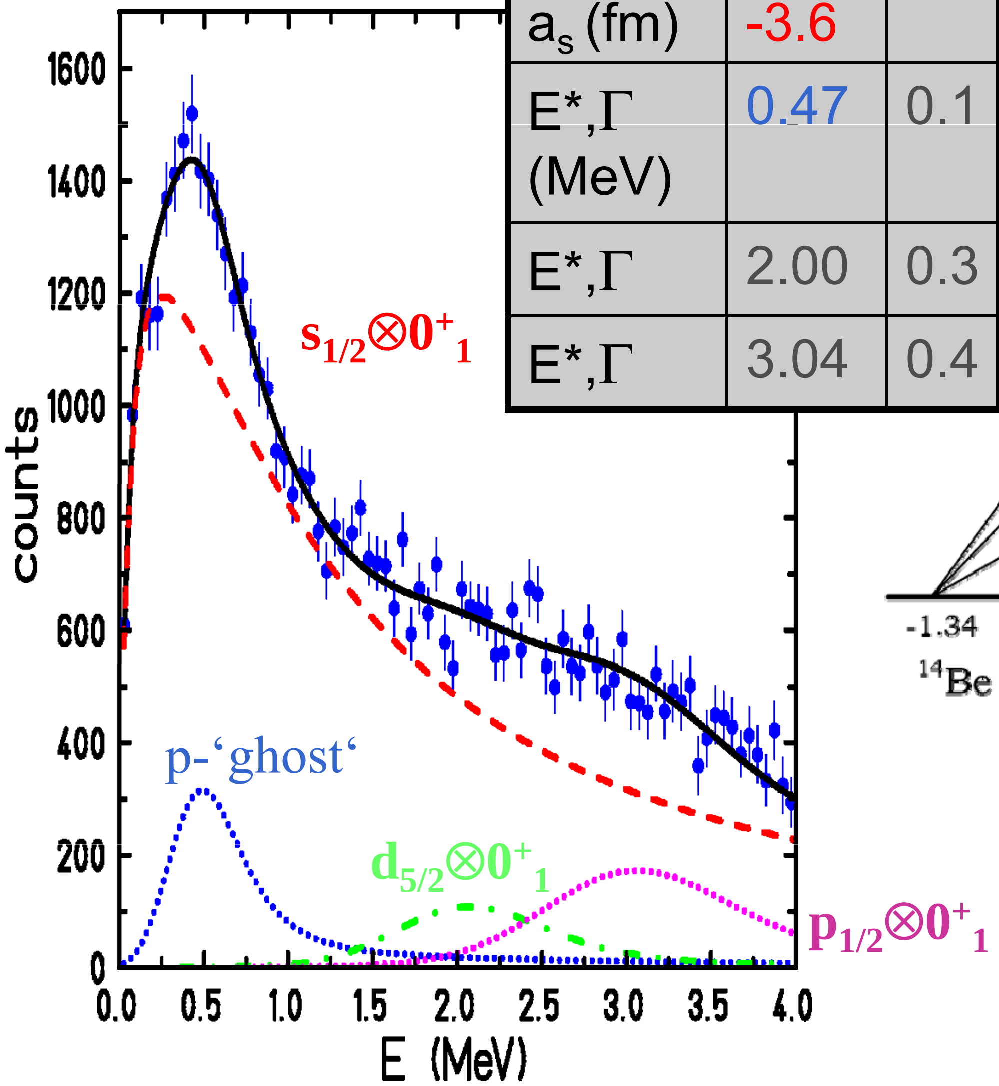
Angular correlations …



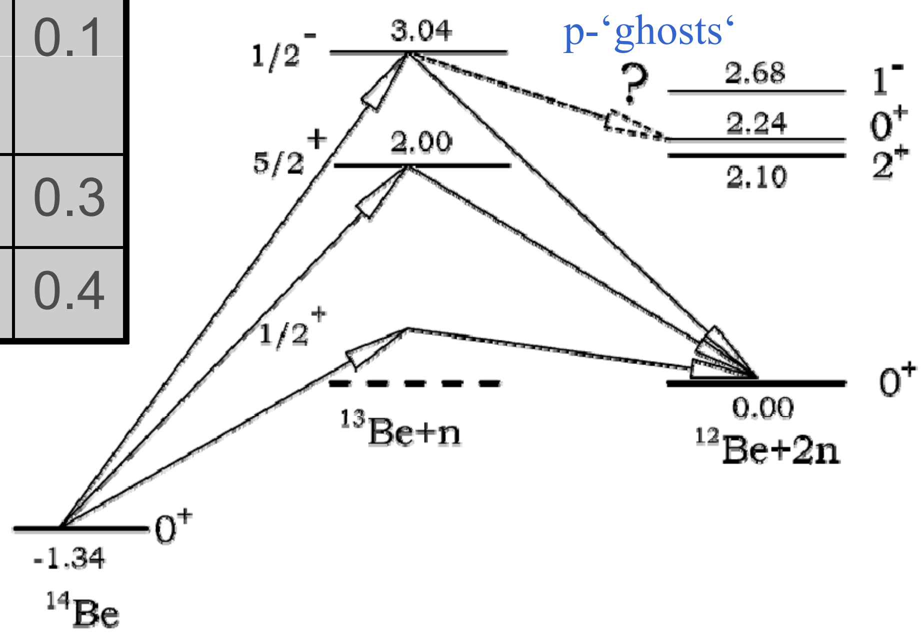
Trying to understand ^{14}Be

➔ ^{13}Be is (too) complicated !

^{13}Be	^{14}Be



a_s (fm)	-3.6	
E*,Γ (MeV)	0.47	0.1
E*,Γ	2.00	0.3
E*,Γ	3.04	0.4



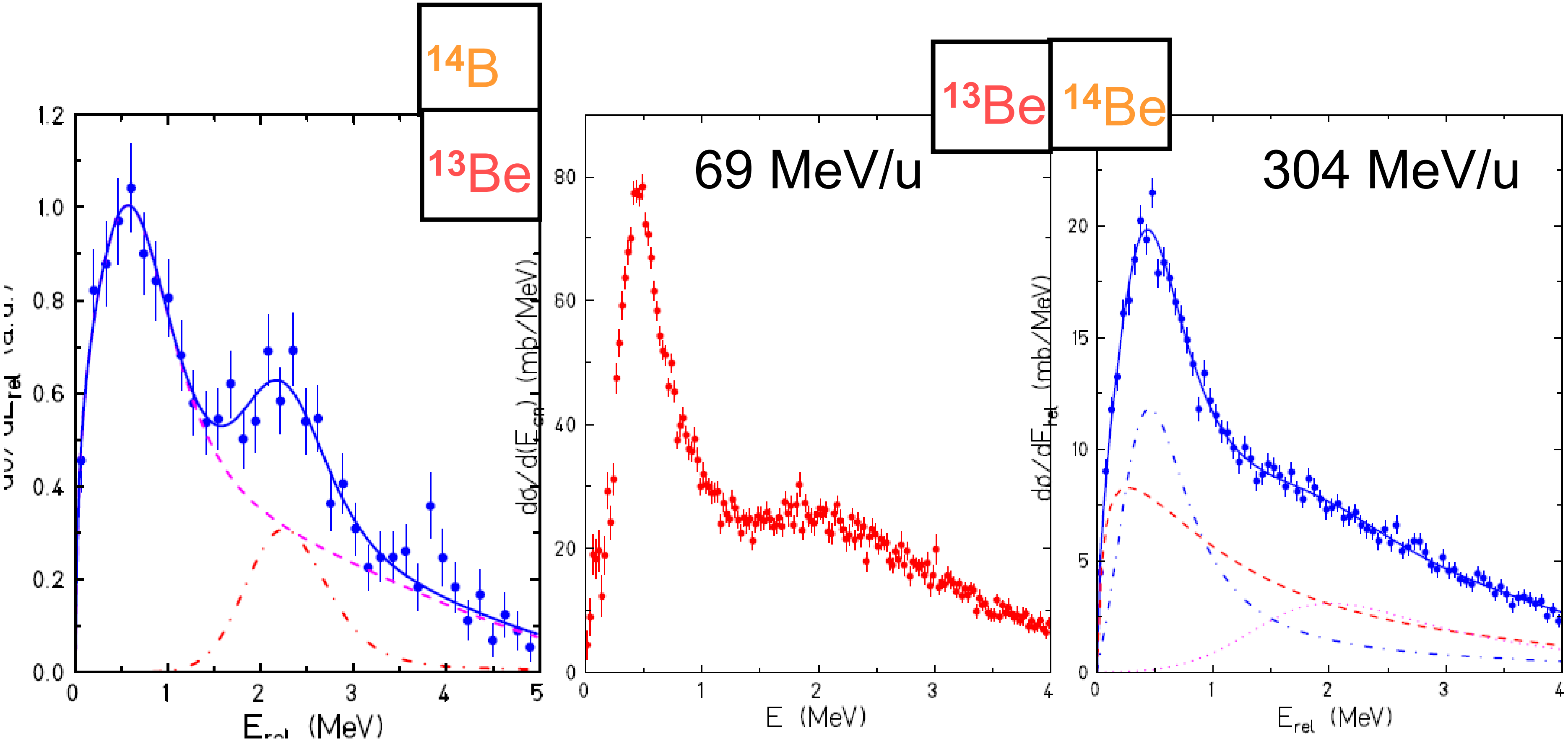
H.S. et al., NUP A 791 (2007) 267

- **Gamma coincidences needed !**
- **Possible inversion confirmed**

Guillaume Blanchon
PHD thesis, Univ. Pisa 2008
http://www.infn.it/thesis/

➔ **^{14}Be structure is puzzling !**

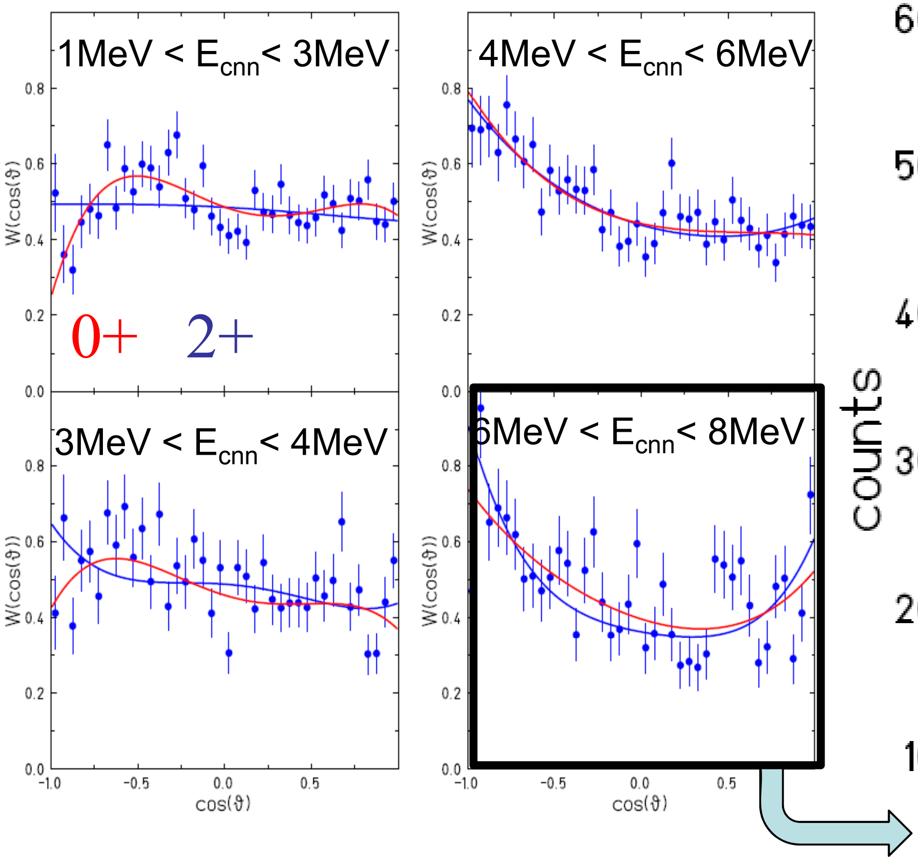
Idea: Understand ^{13}Be by populating it from ‚known‘ systems and at different energies

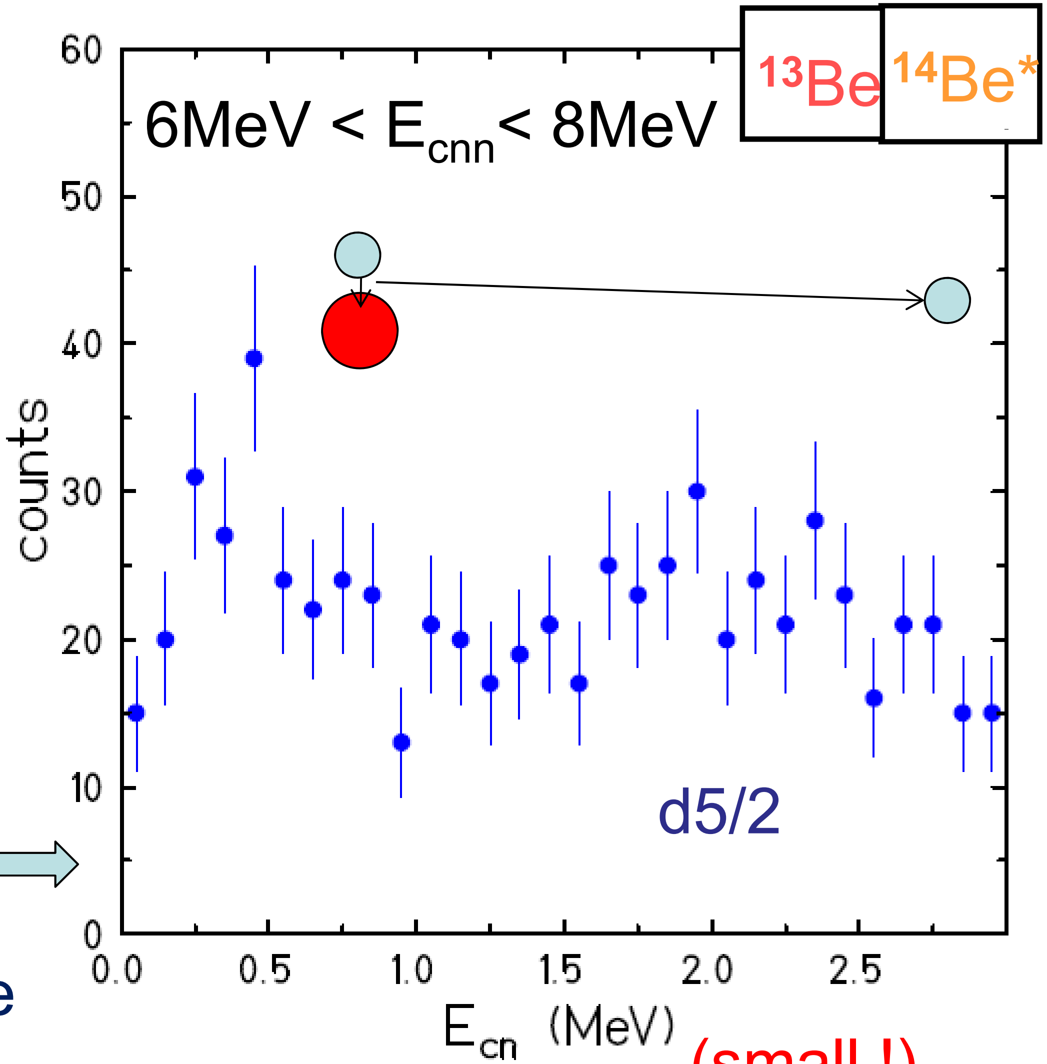


→ d5/2

Kondo, PLB690(2010)245
Fortune, Sherr, PRC82(2010)064302

Idea: Understand ^{13}Be by having it inside a ‚known' system i.e. ^{14}Be*

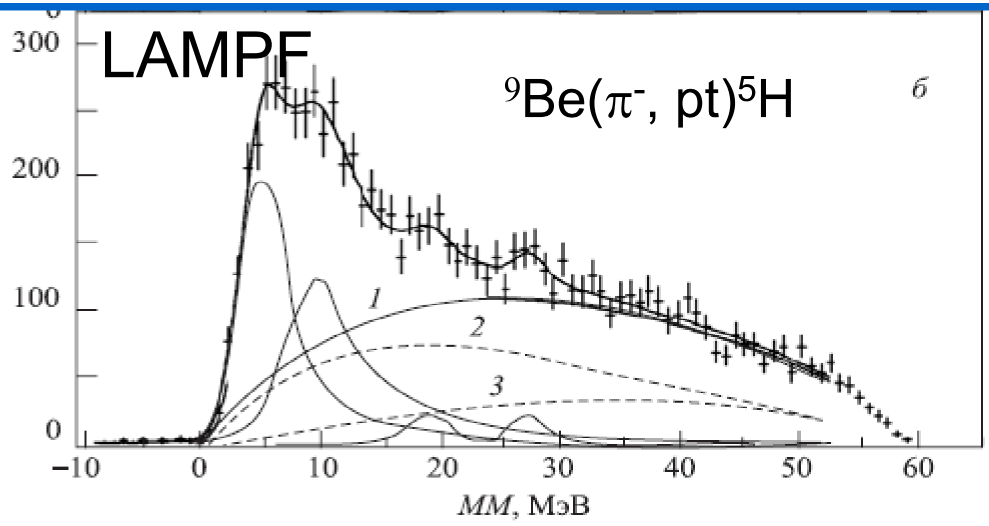


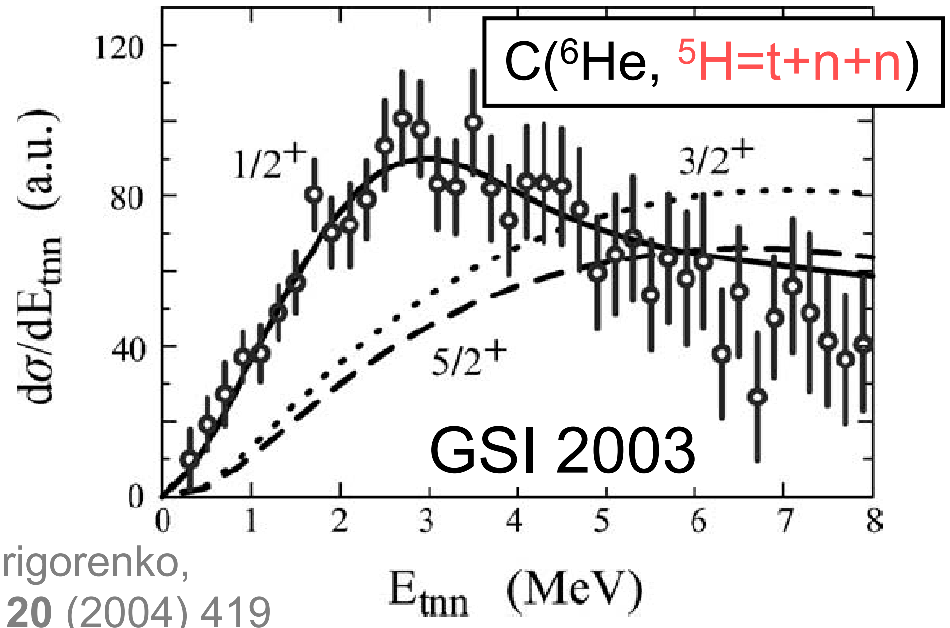


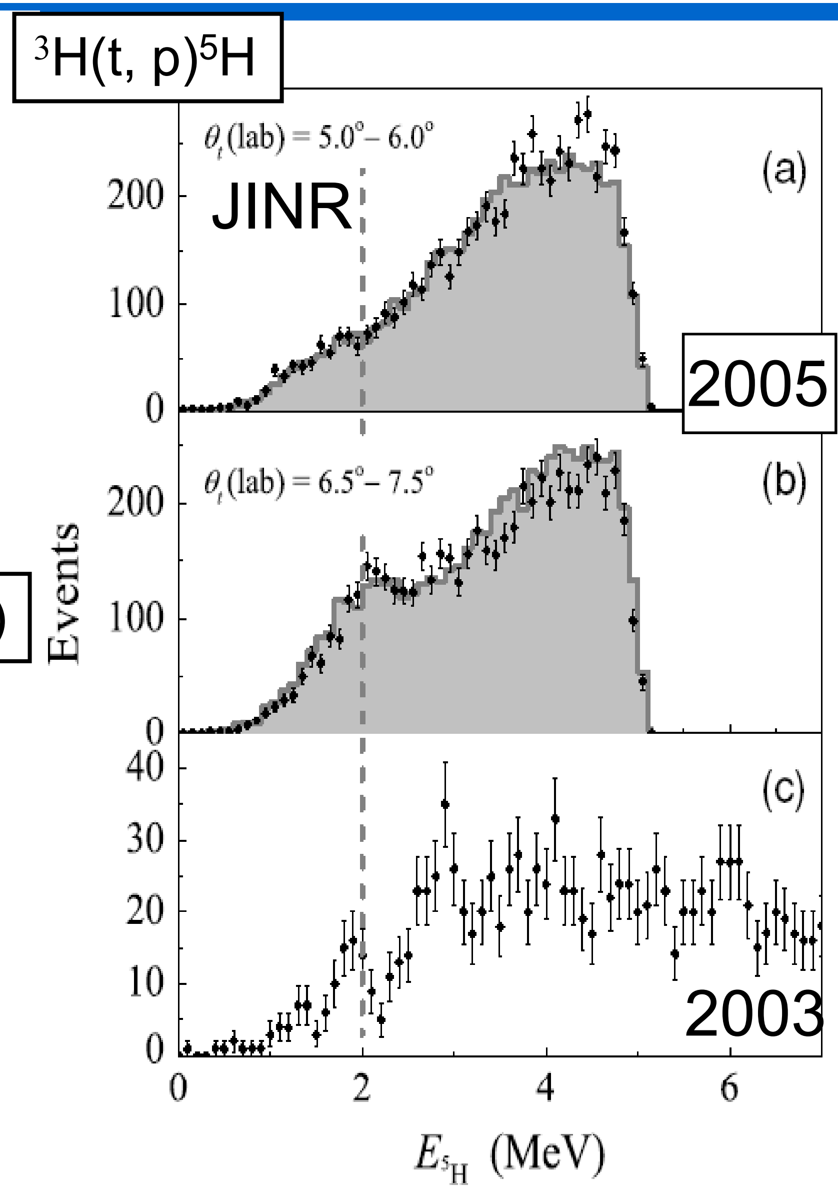
➔Results not yet conclusive ongoing work…

FIN

Beyond the dripline: ^{5}H (just) energy spectra







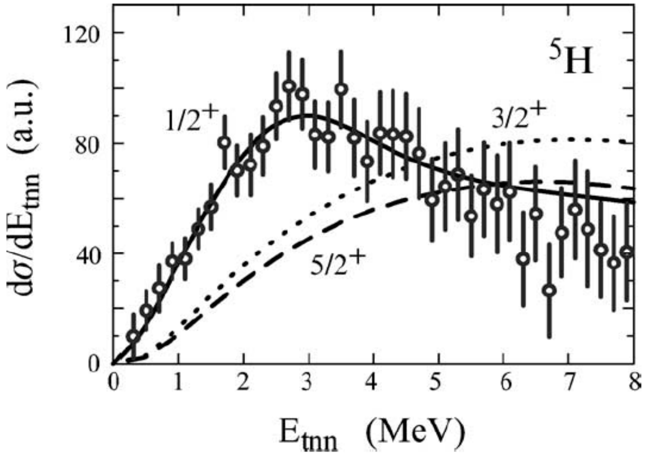
➔L. Grigorenko,
EPJ **A 20** (2004) 419

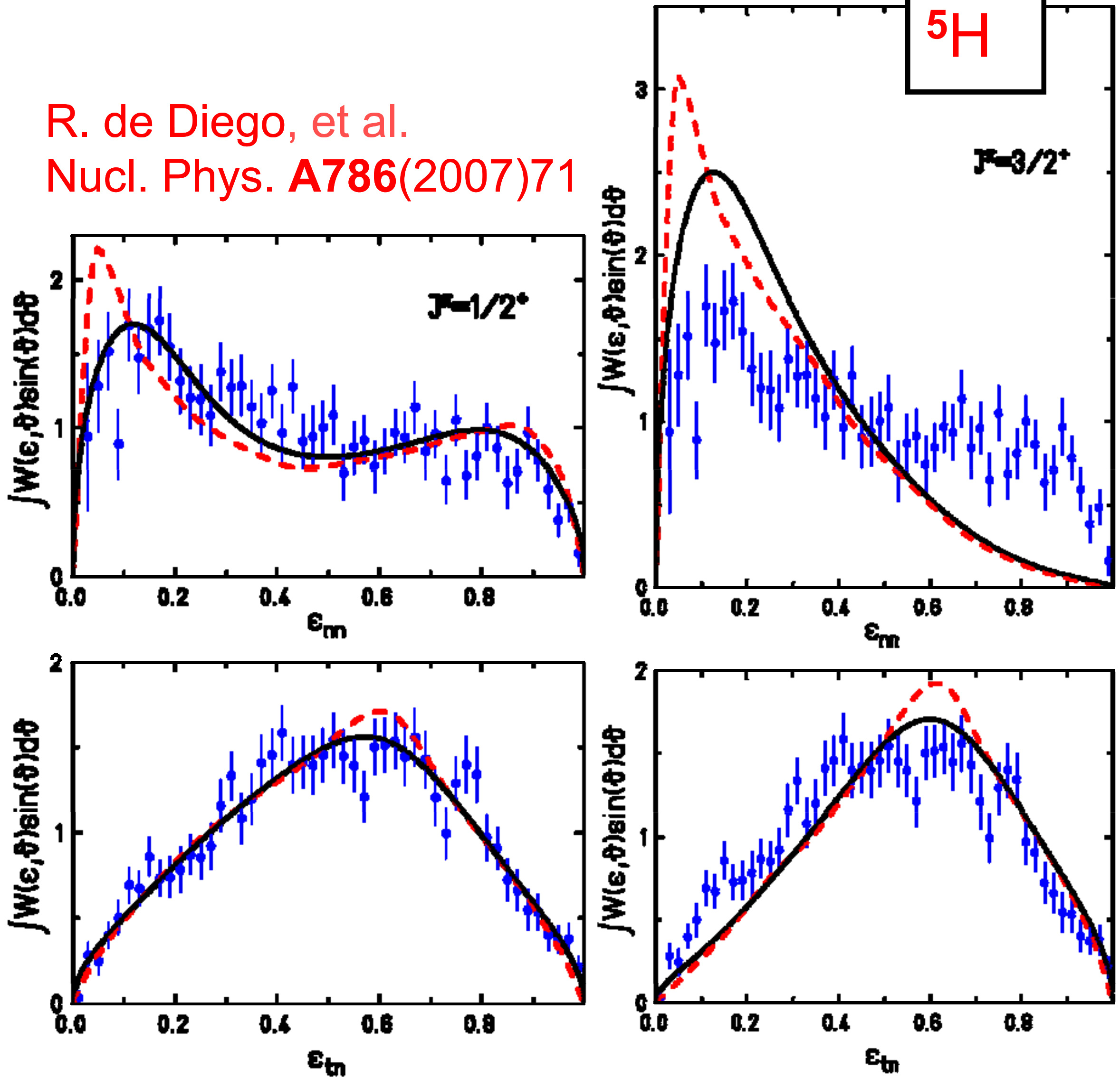
Beyond the dripline: ^{5}H interpretation

^{6}He

^{5}H

R. de Diego, et al.
Nucl. Phys. **A786**(2007)71





Data:

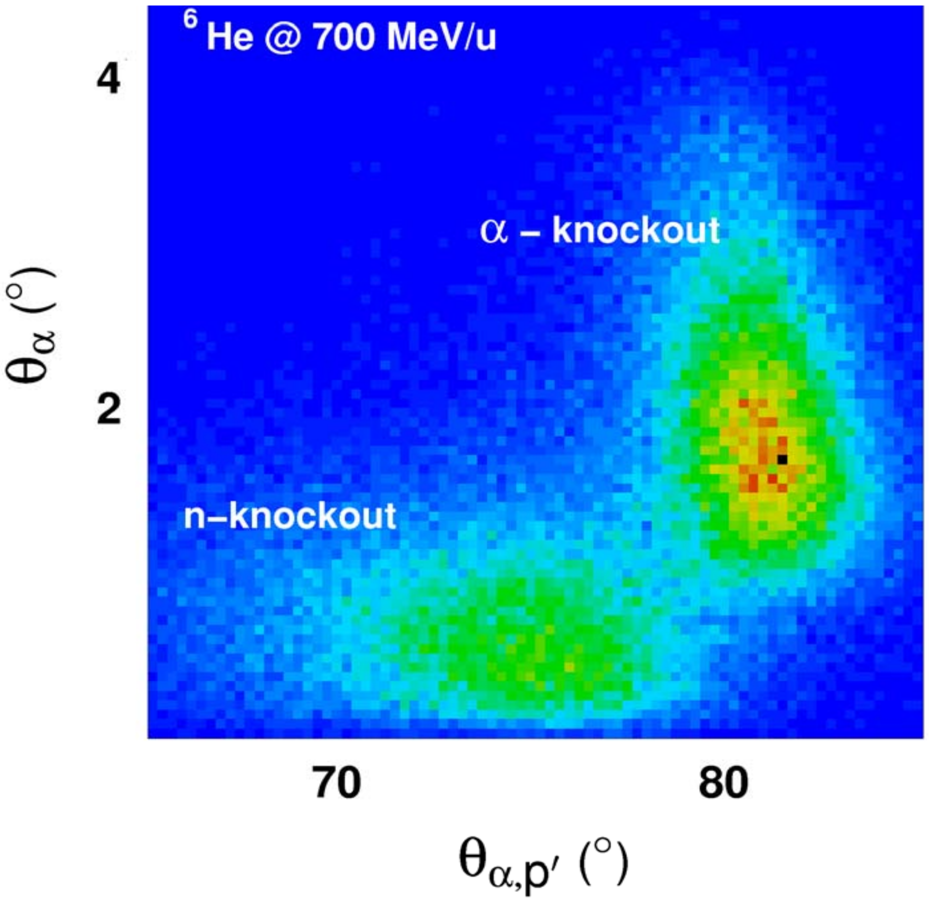
Nucl. Phys. **A723** (2003) 13

Microscopic calculation:

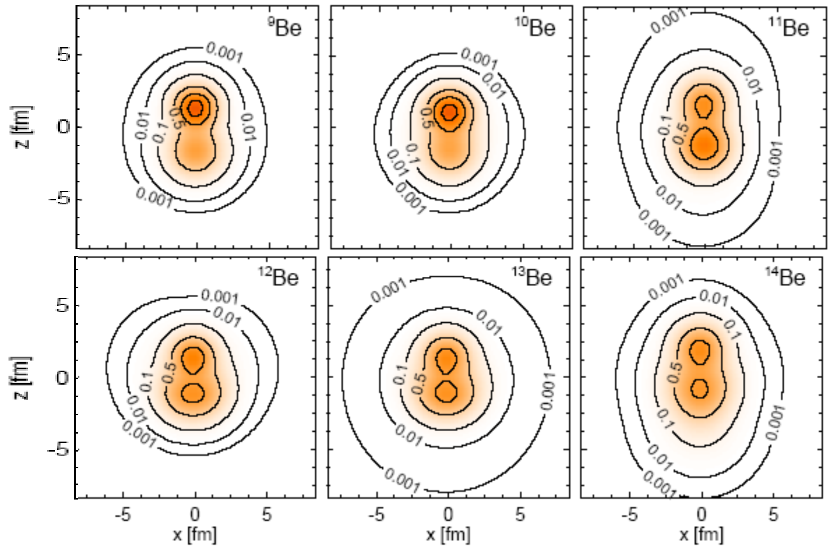
Phys. Rev. **C62** (2000) 014312

What next ? Target recoil detection !

L.V. Chulkov et al., Nucl. Phys. **A759**(2005)43



T. Neff et al., Nucl. Phys. **A752**(2005)321c



liquid hydrogen or CH_2 target
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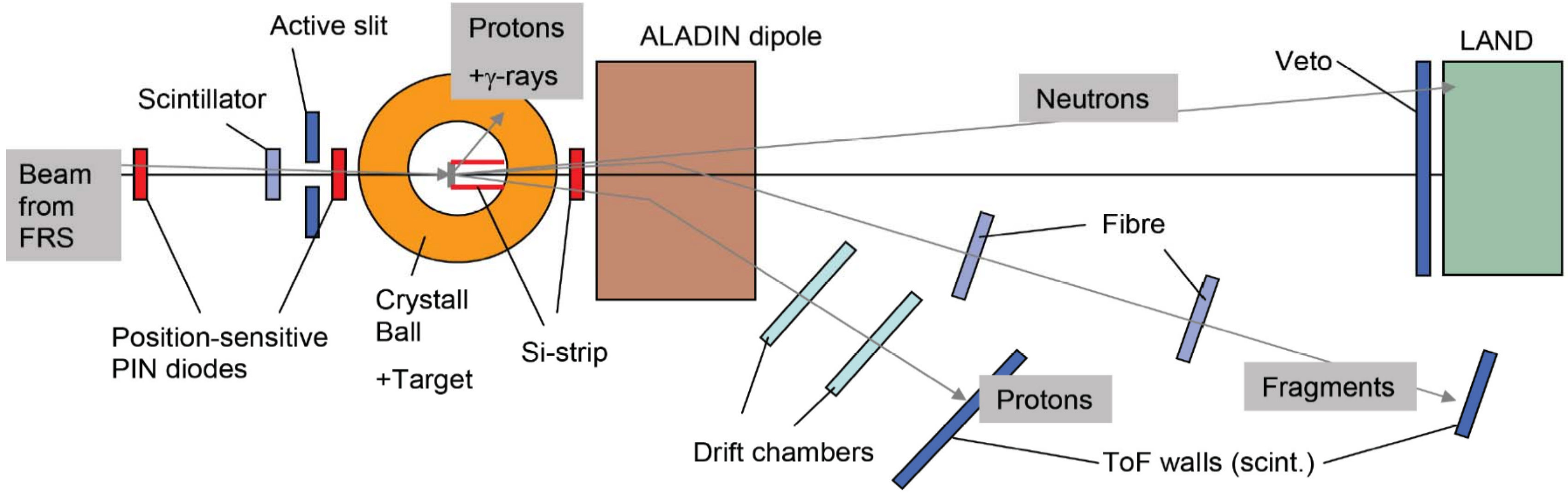
Direct observation of kinematical correlations →

(i) (Cluster) spectroscopic factors
(p,2p),(p,pn),(p,px) inv. kinematics

(ii) clean production of ^{4}H, ^{7}H,…
via **α** knockout !

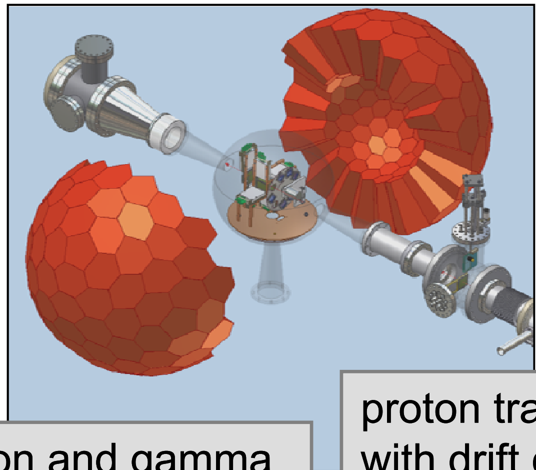
New Experiments (Aug/Sep 2010)

R³B/FAIR precursor: Setup at Cave C

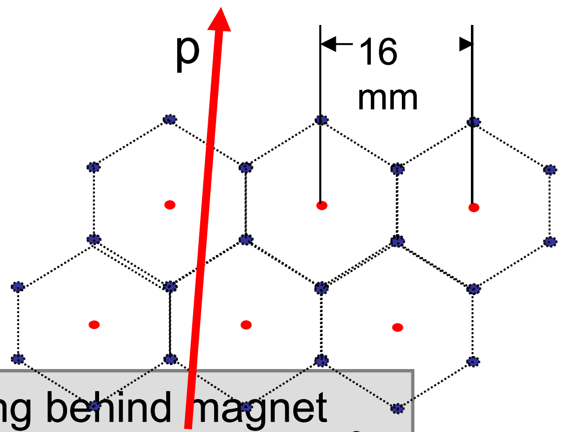


(p,2p) CH_2 target
Coulomb Diss. Pb

Exp S393
Neutron-rich nuclei at
and beyond the dripline



proton and gamma detection



proton tracking behind magnet with drift chambers (100×80 cm^2)
resolution ~200 μm

Aims of the S393 Experiment

Five physics topics using rare-isotope beams will be studied:

I. r-process nucleosynthesis
II. spectroscopy of valence and deeply bound nucleons in exotic nuclei
III. isospin dependence of nucleon-nucleon correlations
IV. alpha clustering in exotic nuclei
V. spectroscopy of unbound nuclei

Run as single experiment by R3B Collaboration:

- same experimental setup for all topics (Cave C $\rightarrow$ R^3B)
- same settings of FRS for all topics
- Use different reactions ($\Rightarrow$ targets) dependent on topic:
  - heavy-ion induced electromagnetic excitation (Pb target)
  - (p,2p), (p,pn) and (p,pα) quasifree scattering (proton in CH_2 target)
  - one- and two-neutron removal (Carbon in CH2 target)

Maximise efficiency of beam time

R3B – Cave C time schedule

2010 Integration of new CB readout electronics – New trigger electronics

Exp S393 Neutron-rich nuclei at and beyond the dripline

Wiescher 60Fe

Remaining shifts Datta Pramanik

Integration of LAND Taquila readout

2011 NeuLAND prototype production

d,t(p,2p)n,2n Exp – Critical Test/Calib NeuLAND / LAND

New heavy-ion tracking system

Exp: Pygmy dipole, GDR, GQR in Sn isotopes

New low-energy neutron detector

Exp: charge-exchange – GTR Astro; spin-dipole

2013 Dismount ALADIN, New superconducting dipole **ALADIN in Cave B?**

production of 20% NeuLAND

2014 R3B – phase 1 commissioning and first experiment

2014 – 2015 stepwise upgrade to final R3B plus experimental programme

Planned experiments of other collaborations in Cave C

IKAR, HYPHI, Asy-EoS, FIRST/SPALADIN

FPGA logics

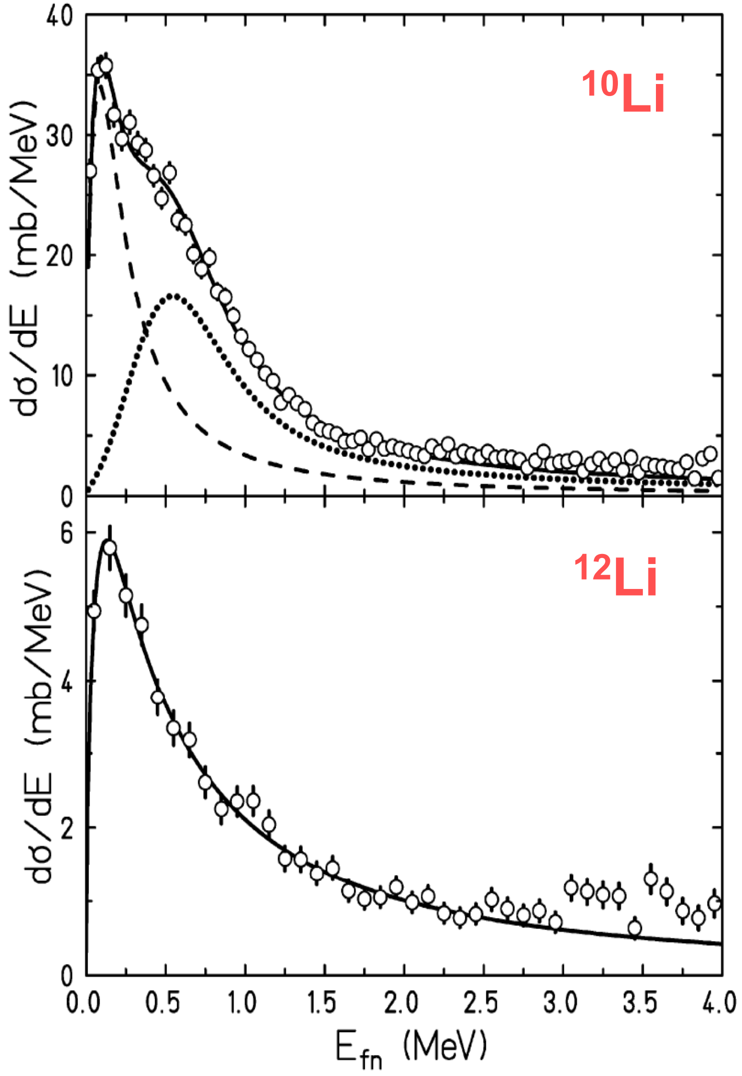
Shap. QDC

Online PSA

Open firmware

Exploring Unbound Lithium isotopes

^{9}Li	^{10}Li	^{11}Li	^{12}Li	^{14}Be



$$d\sigma/dE_{fn} \propto p_{fn} (k^2+p_{fn}^2)^{-2} [\cos(\delta) + k/p_{fn} \sin(\delta)]^2$$

$$p_{fn} \cot(\delta) = -1/a + 1/2\, r_0\, p_{fn}^2 + \ldots \mid k = \mathrm{sqrt}(2\,\mu\, S_n)$$

Bertsch, Hencken, Esbensen, PR**C57**(1998)1366

a_s (fm)	E*(MeV)	Γ(MeV)
-22.4(4.8)	0.57(2)	0.55(3)

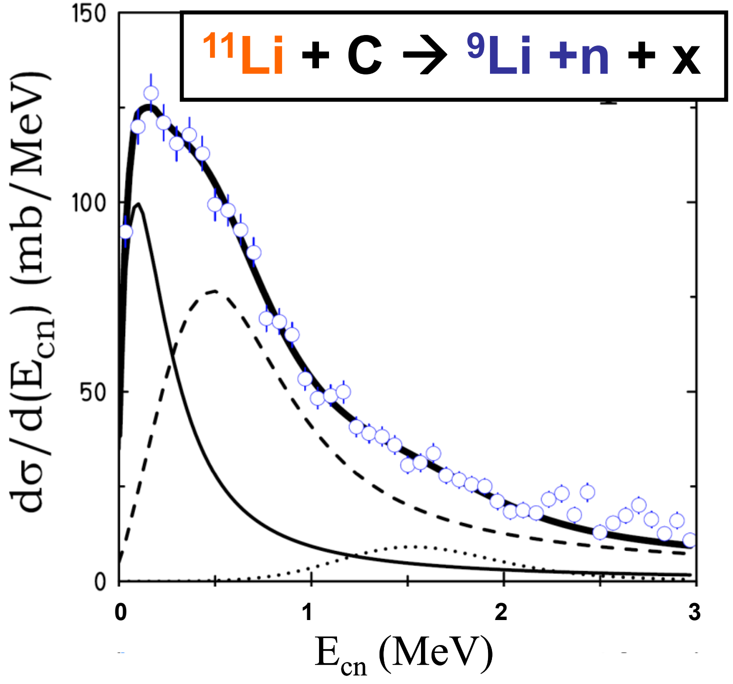
S_n 0.35(22) ≈ S_{2n} ^{11}Li

a_s (fm)	S_n(MeV)
-13.7(1.6)	1.47(0.19)

Close to S_{2n} ^{14}Be

Y. Aksyutina, H. Johansson et al., PL**B666** (2008) 430

^{11}Li → ^{10}Li: Combined Results



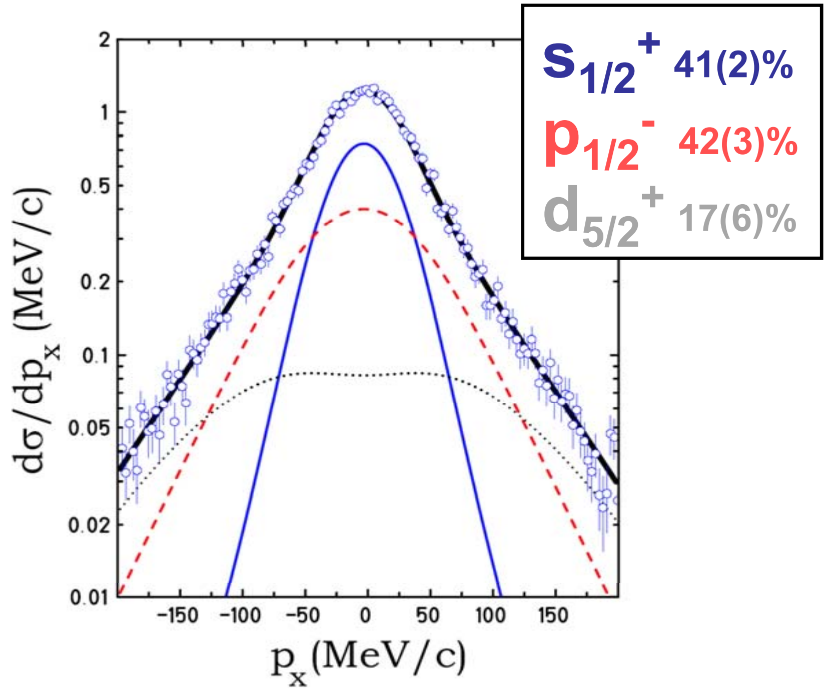
H.S. et al.,
Phys.Rev.Lett. **83** (1999) 496
Nucl. Phys. **A 791** (2007) 267

→Confirmed eg @ GANIL
^{11}Be, ^{14,15}B → ^{9}Li+n
H. Al Falou et al. Niigata 2010

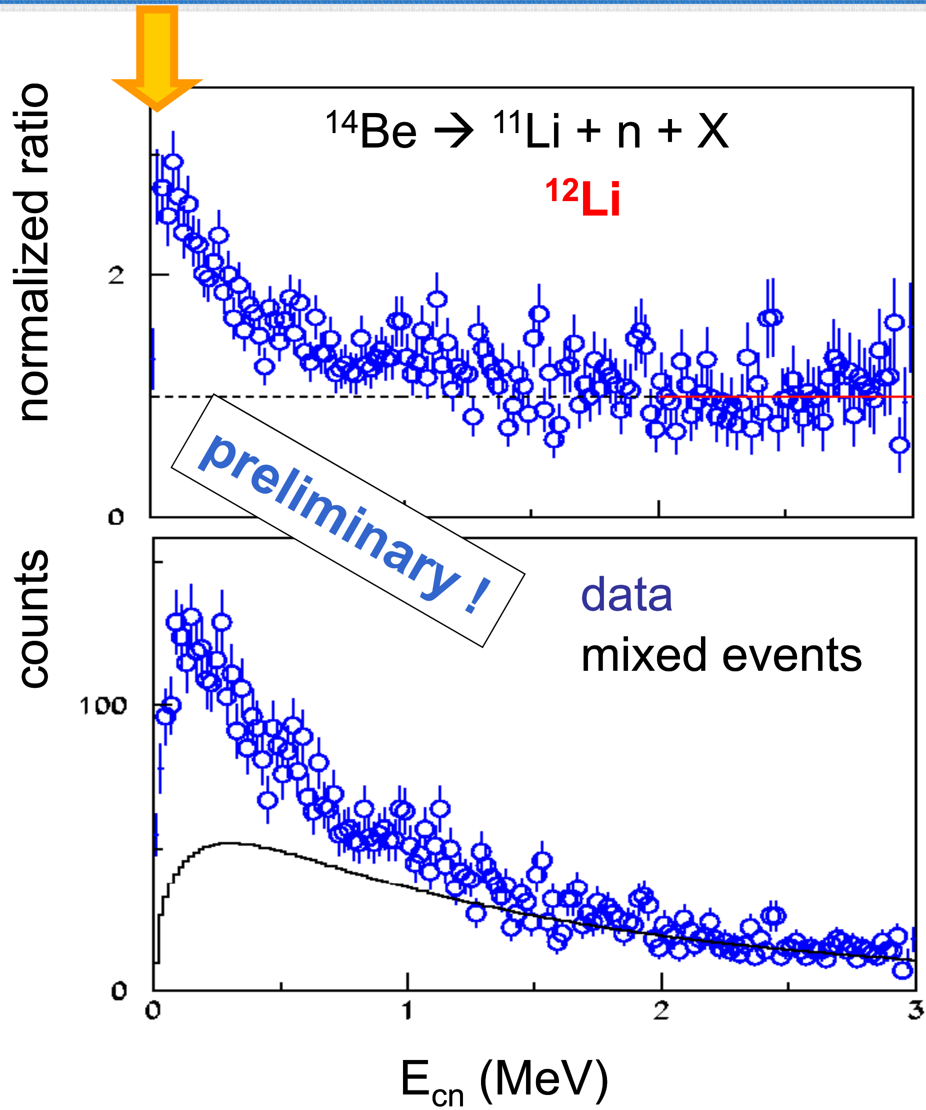
$-30\ ^{+12}_{-31}$ fm;	virtual state
0.51(44); 0.54(16)	E*; Γ
1.49(88); < 2.2	in MeV

(−22.4(4.8) fm / 0.566(14) MeV lH_2 target)

- supported by ang. correlations

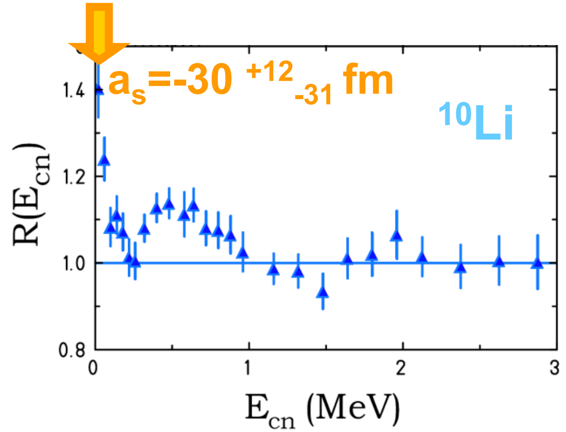


Unbound Lithium isotopes: ^{12}Li



➔ strongly correlated events !

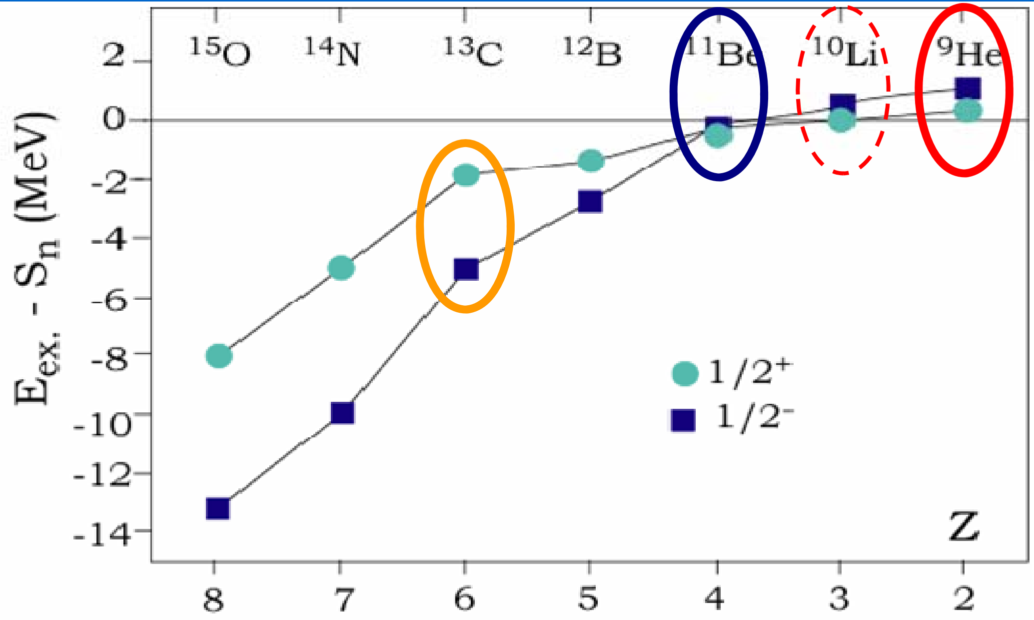
➔ no two components as in ^{10}Li



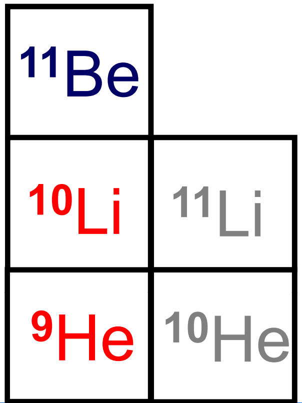
➔steep rise at treshold

➔ **virtual scattering state**

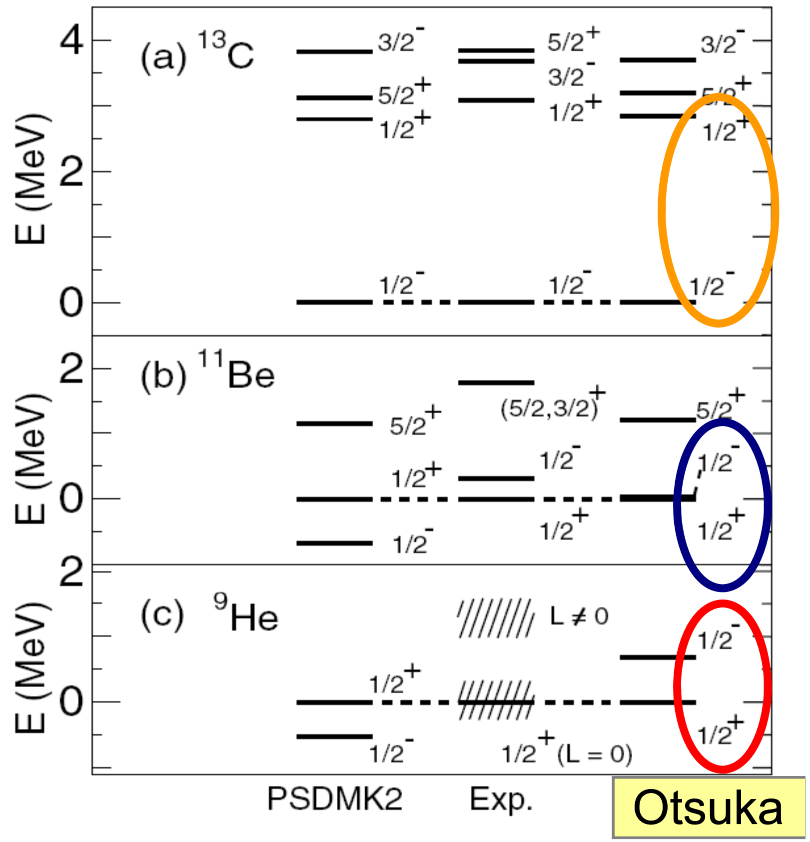
Intruder states e.g. N=7



I. Talmi, I. Unna, PRL4 (1960) 469
B. Jonson, Phys. Rep. 389 (2004) 1



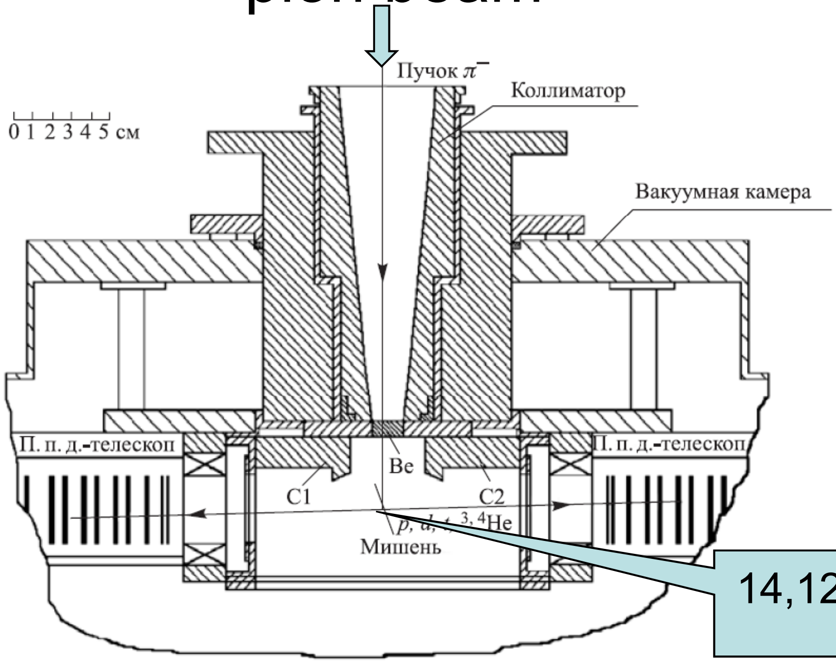
T. Otsuka *et al.* ,
Phys. Rev. Lett. 87 (2001) 082502



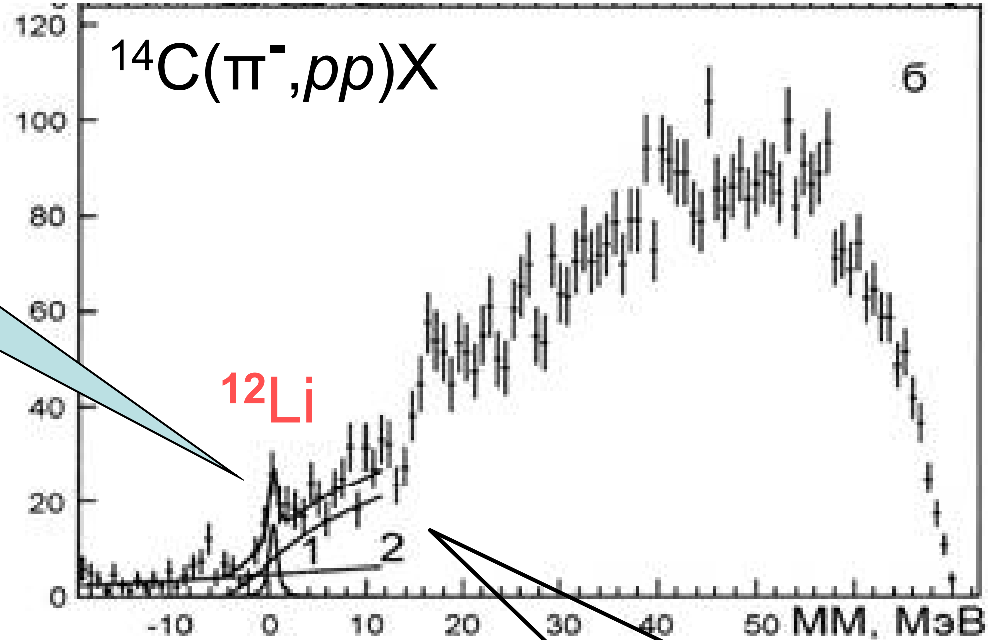
Exploring Unbound Lithium isotopes

$E_R \approx 4{,}2$ МэВ,
$\Gamma \approx 1{,}5$ МэВ.

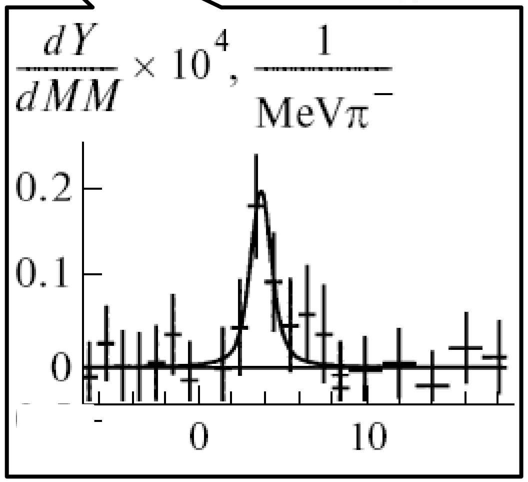
pion beam



^{14,12}C target



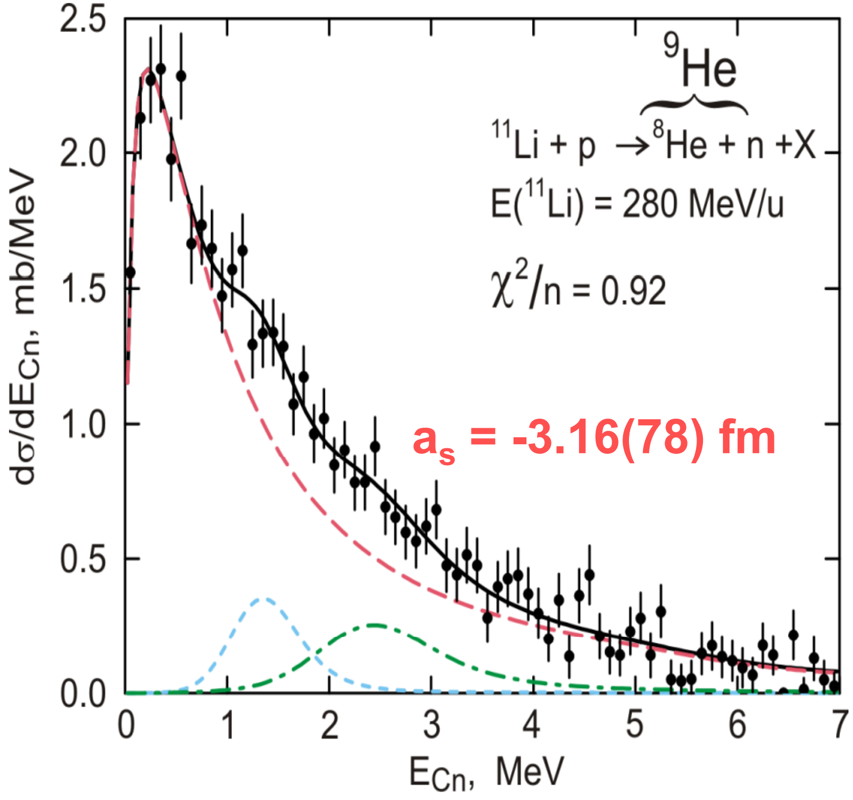
Yu.B.Gurov, et al.,
Bull. Rus. Acad.
Sci. Phys. **74**,
(2010) 433



Constraints on ^{9}He via ^{10}He **g.s.** …

^{11}Li

^{9}He



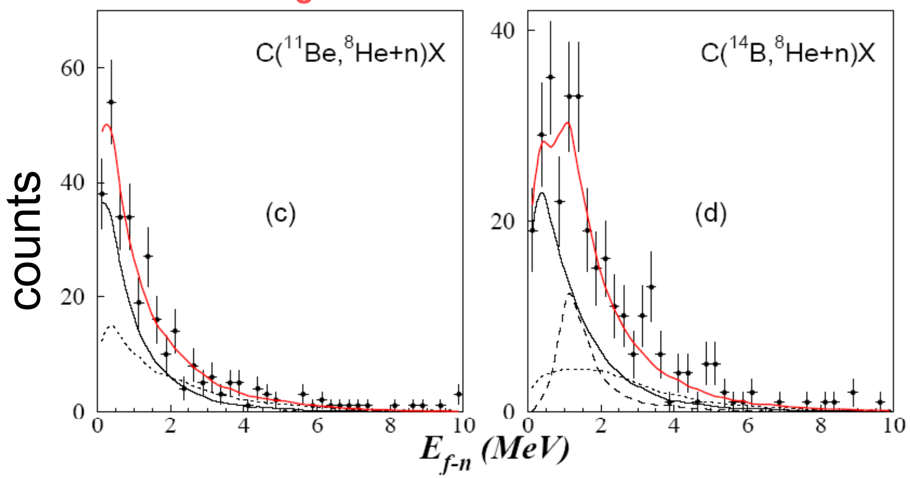
E_r=1.33(8) MeV, Γ=0.1 MeV
E_r=2.4 MeV, Γ=0.7 MeV
Prog.Part. Nucl.Phys. 42(1999)17

H.T. Johansson et al., Nucl. Phys. **A842** (2010) 15

L. Grigorenko, M. Zhukov,
PR**C77** (2008) 034611

^{9}He: a_s < -5fm ↔ ^{10}He g.s. at threshold

GANIL a_s = - 3 .. 0 fm

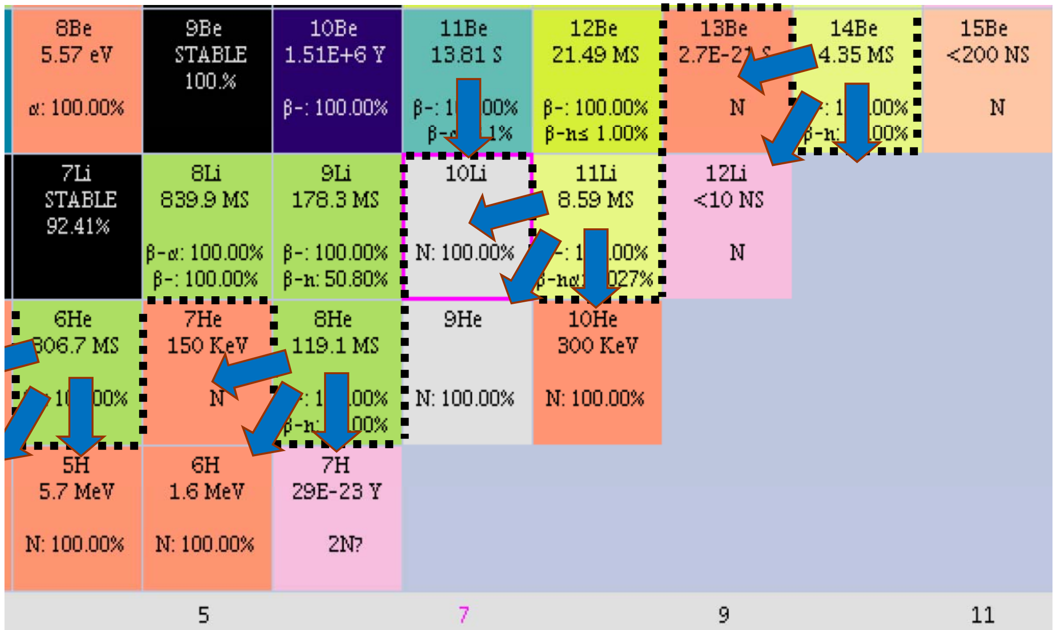


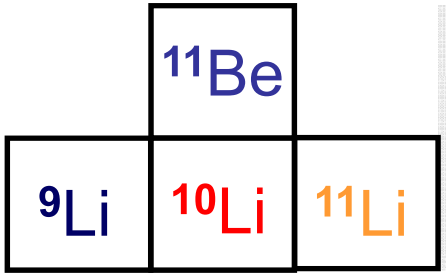
A. Falouh et al., Niigata Conf. 2010

Exotic structure across the dripline:

P.G. Hansen, Nature 328 (1987) 476

R. Anne et al., Nucl. Phys. **A575**(1994)125

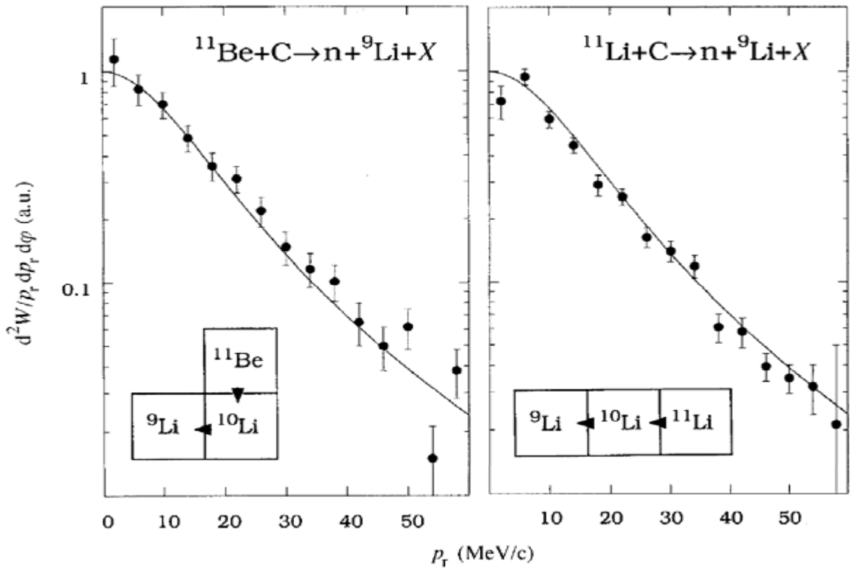




1n-halo

p/n knockout

2n-halo



➔ **most exotic systems**

➔**nearly unbiased & clean production !**

B. Jonson, K. Riisager ➔ **FSI**

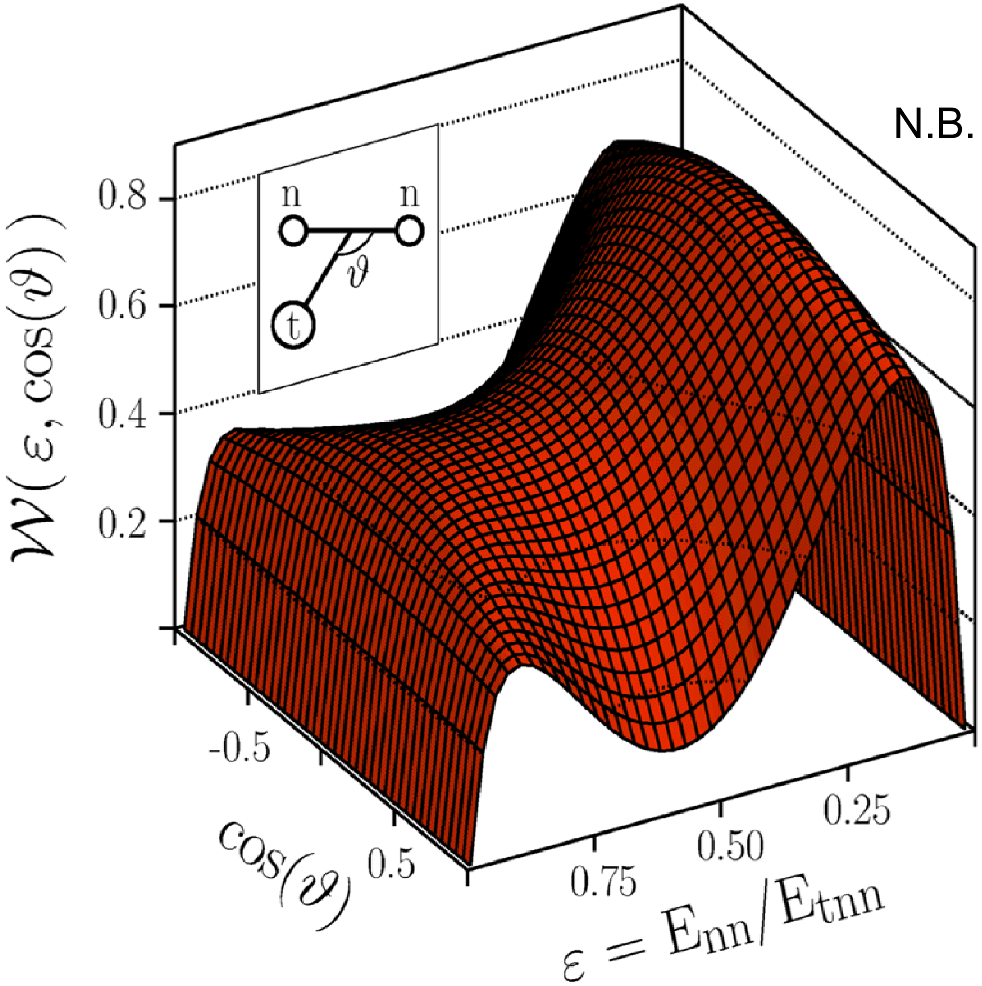
Phil. Trans. R. Soc. Lond. A **356** (1998) 2063

Beyond the dripline: ^{5}H correlations

^{6}He
^{5}H

^{6}He +C → t+n+n : proton knockout from ^{6}He core

M. Meister et al., PRL **91**(2003)162504
N.B. Shulgina et al., Phys.Rev. **C62** (2000) 014312

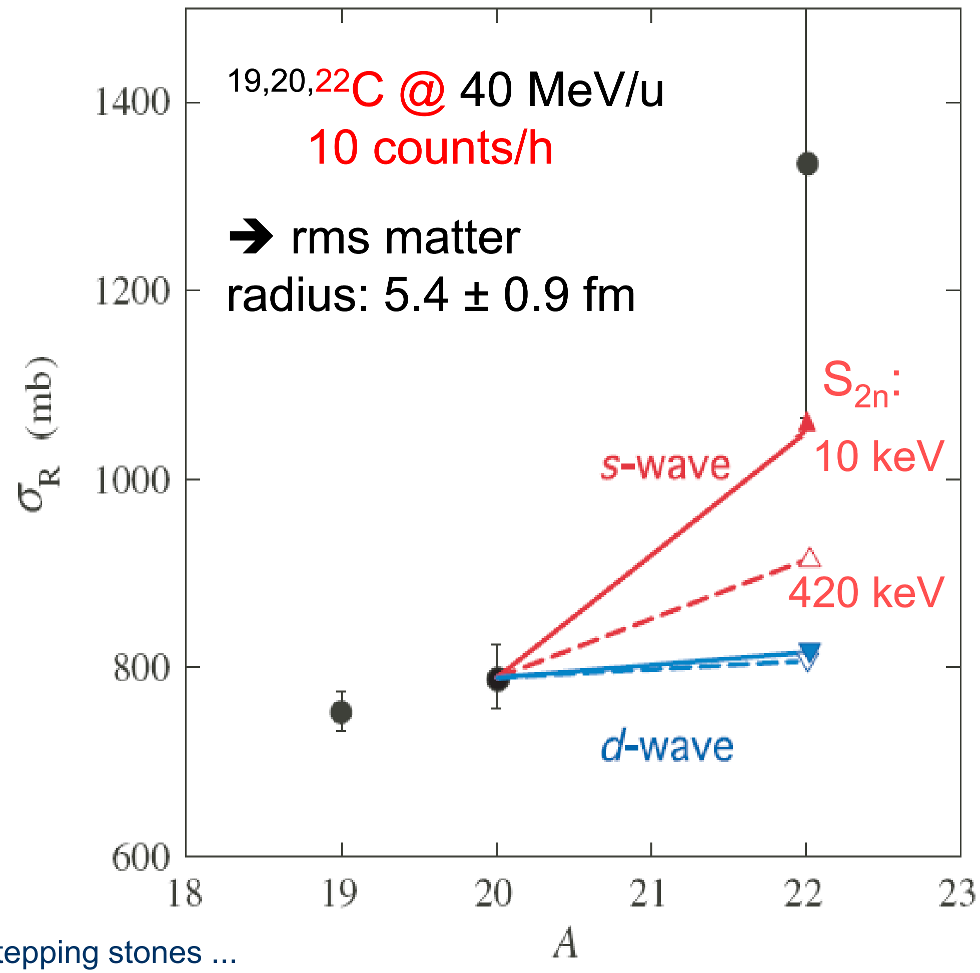


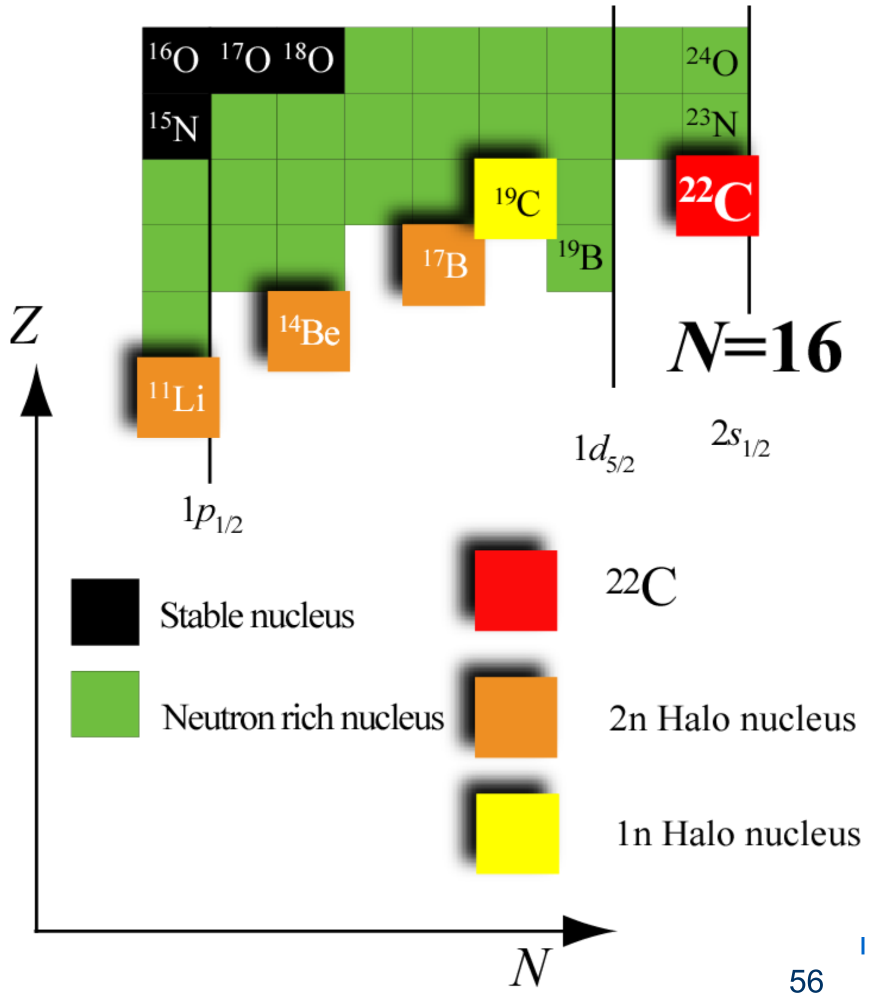
- ✔ $\mathcal{W}(\varepsilon, \vartheta)$ reconstructed
  from 2 × 2 projections
- ✔ confirmation of $J^\pi = 1/2^+$
  for the t+n+n g.s. conf.
  probability > 63(4) %
- ✔ structural similarity to ^{6}He
  $\nu(p_{3/2})^2$ about 80 % 93%

Observation of a Large Reaction Cross Section in the Drip-Line Nucleus ^{22}C

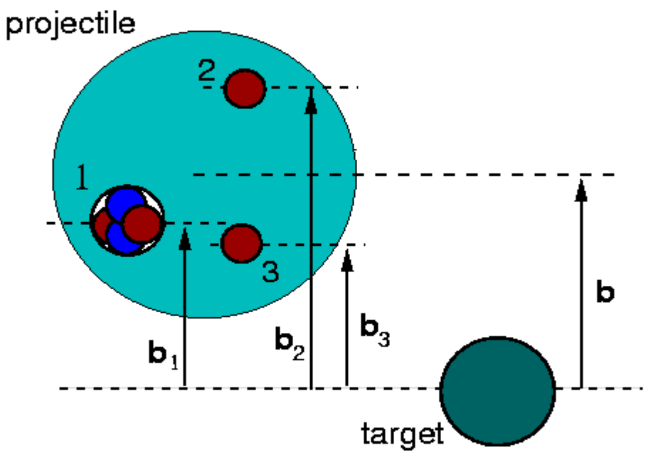
K. Tanaka,[1] T. Yamaguchi,[2] T. Suzuki,[2] T. Ohtsubo,[3] M. Fukuda,[4] D. Nishimura,[4] M. Takechi,[4,1] K. Ogata,[5] A. Ozawa,[6] T. Izumikawa,[7] T. Aiba,[3] N. Aoi,[1] H. Baba,[1] Y. Hashizume,[6] K. Inafuku,[8] N. Iwasa,[8] K. Kobayashi,[2] M. Komuro,[2] Y. Kondo,[9] T. Kubo,[1] M. Kurokawa,[1] T. Matsuyama,[3] S. Michimasa,[1,*] T. Motobayashi,[1] T. Nakabayashi,[9] S. Nakajima,[2] T. Nakamura,[9] H. Sakurai,[1] R. Shinoda,[2] M. Shinohara,[9] H. Suzuki,[10,6] E. Takeshita,[1,†] S. Takeuchi,[1] Y. Togano,[11] K. Yamada,[1] T. Yasuno,[6] and M. Yoshitake[2]

PRL 104 (2010) 062701





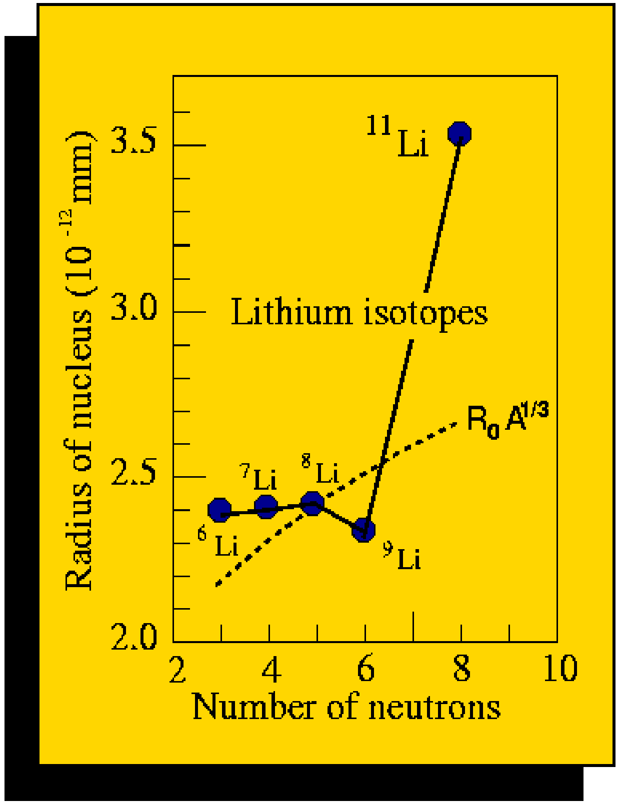
Caveat: Interaction cross sections



Al-Khalili& Tostevin, PRL76 (96) 3903

R(^{11}Li) = 3.53(10) fm

(Tanihata: 3.10(14) fm)



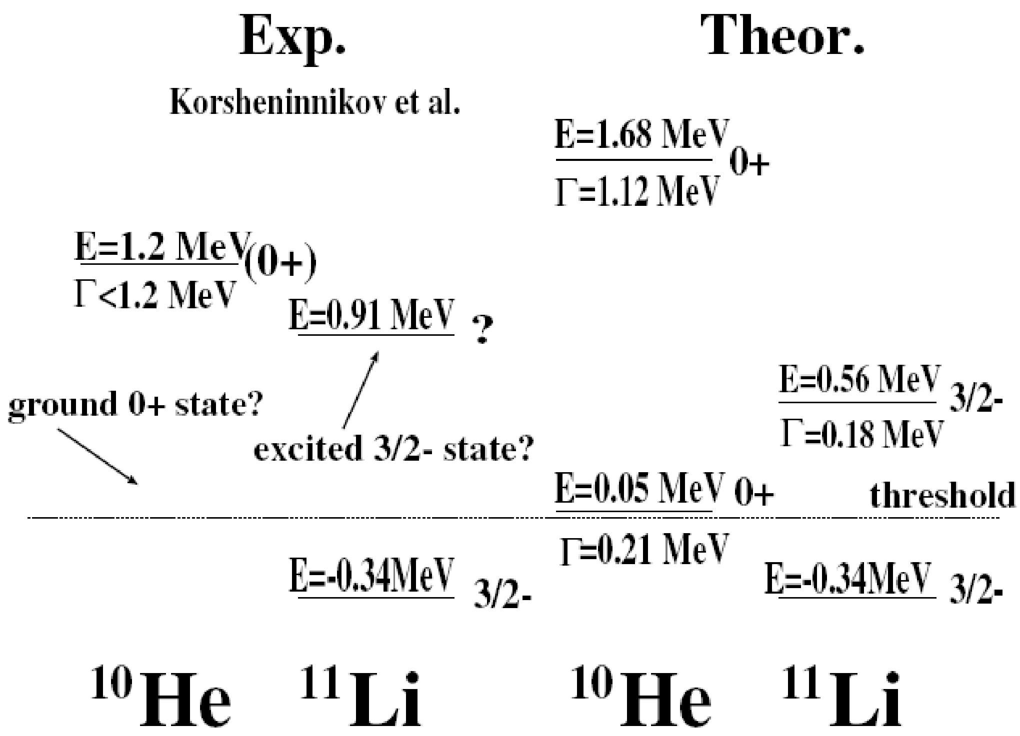
Correlations change interpretation
i.e. R extracted from σ_I

Getting neutron rich … ^{10}He

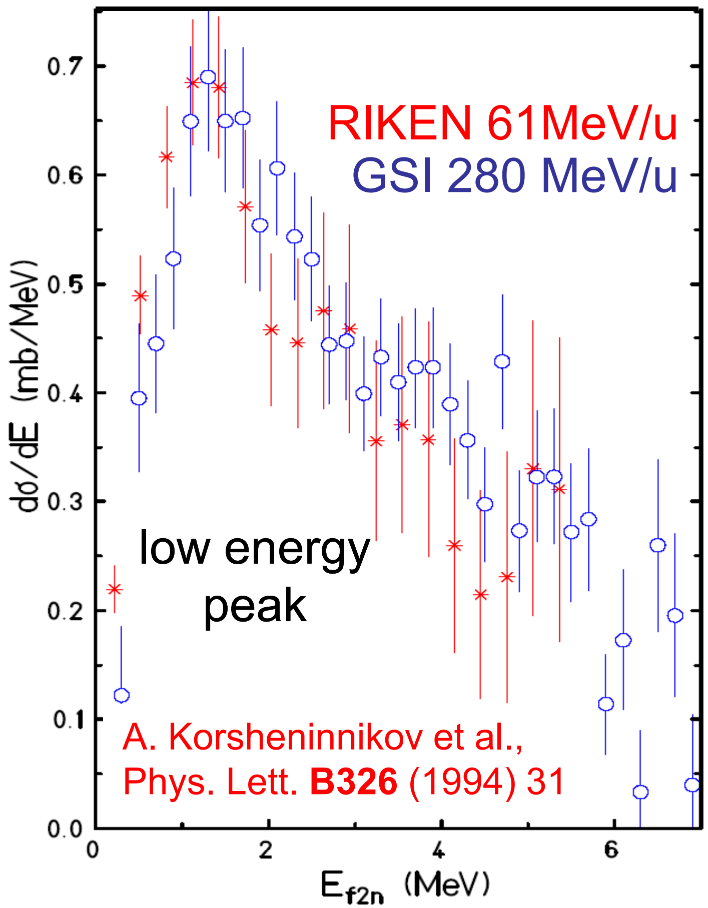
^{11}Li

^{10}He

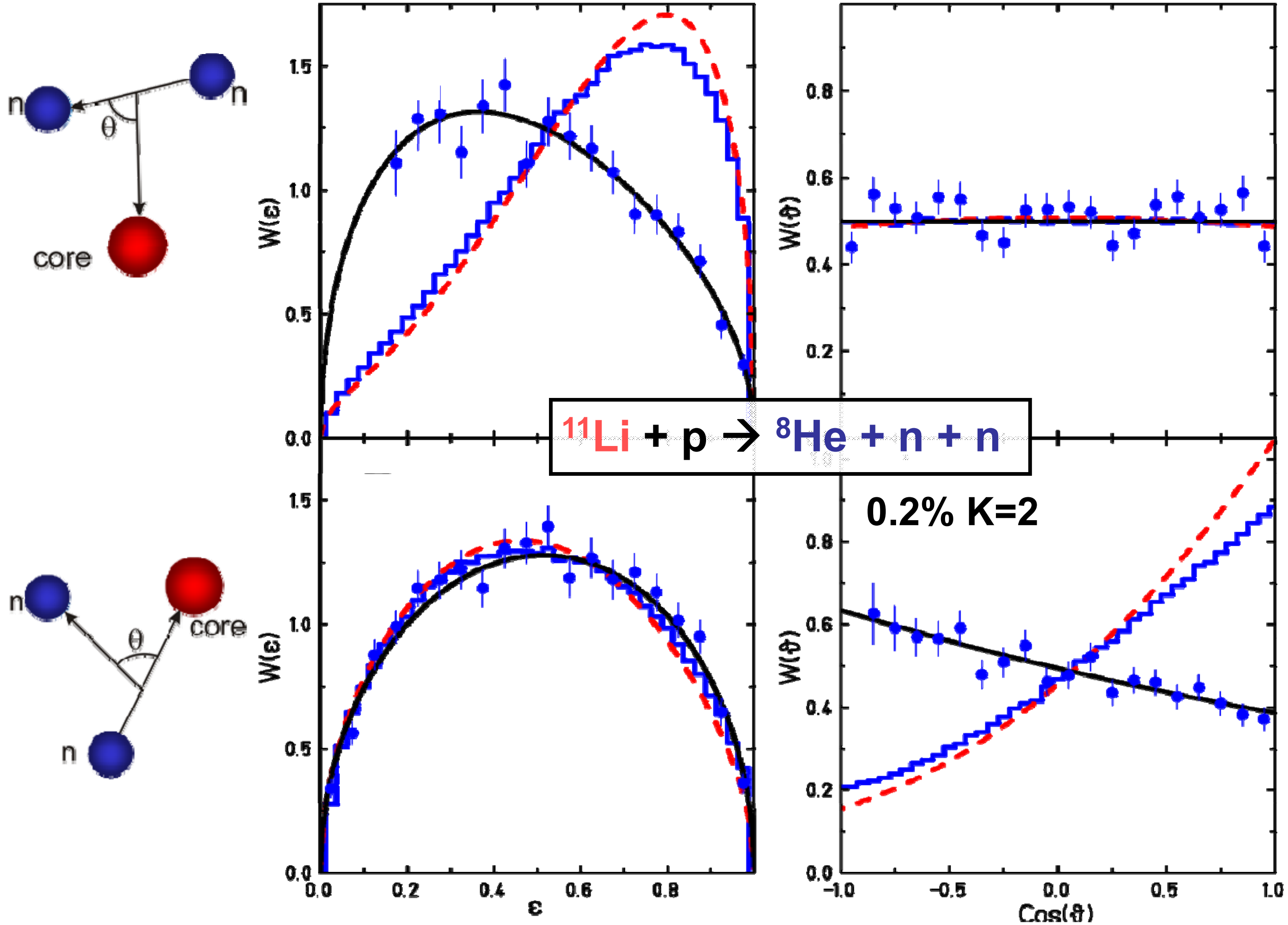
Shigeyoshi Aoyama, PRL**89** (2002) 052501
possible similarity of ^{10}He and ^{11}Li g.s.



^{11}Li + p/CD$_2$,C → ^{8}He + n + n



Comparison ^{11}Li and ^{10}He via angular correlations



Excitation energy range 1-3 MeV (low energy peak)

- no resemblance to ^{11}Li seed angular correlations

➔ ^{10}He is structurally different

H.T. Johansson, Y. Aksyutina, Nucl. Phys. **A847** (2010) 66

^{11}Li wave function: N.B. Shulgina et al., Nucl. Phys. A825 (2009) 175