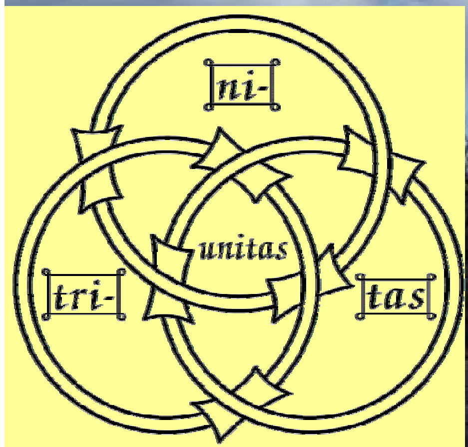
Light ions beyond the dripline

Haik Simon • Gesellschaft für Schwerionenforschung / Darmstadt

Outline

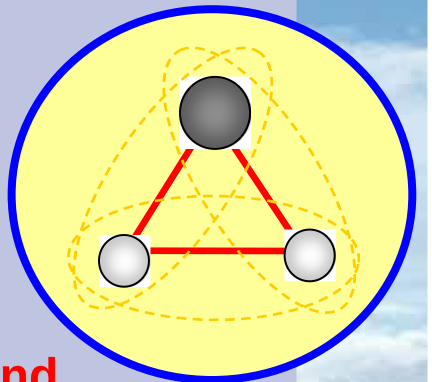
- introduction
- reactions
- halo nuclei
- unbound systems
- summary



Light ions: the lower part of the chart of nuclei

http://www.nndc.bnl.gov/chart/

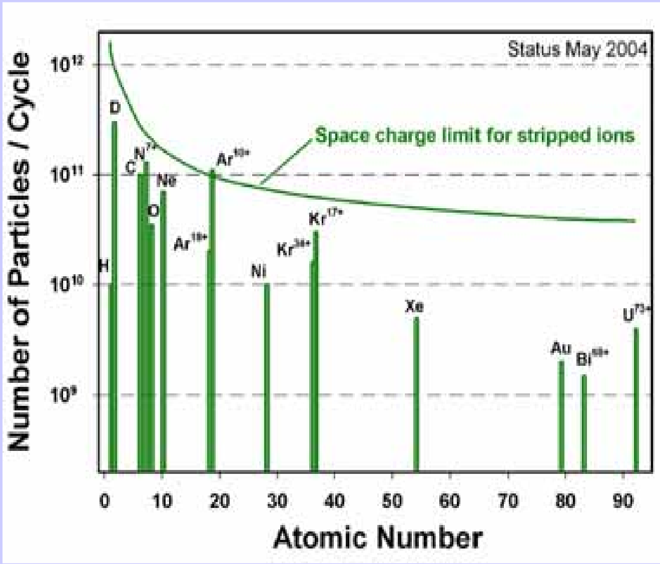
	7Be 53.22 D ε: 100.00%	8Be 5.57 eV α: 100.00%	9Be STABLE 100.%	10Be 1.51E+6 Y β-: 100.00%	11Be 13.81 S β-: 100.00% β-α: 3.1%	12Be 21.49 MS β-: 100.00% β-n≤ 1.00%	13Be 2.7E-21 S N	14Be 4.35 MS β-: 100.00% β-n: 81.00%	15Be <200 NS N
3	6Li STABLE 7.59%	7Li STABLE 92.41%	8Li 839.9 MS β-α: 100.00% β-: 100.00%	9Li 178.3 MS β-: 100.00% β-n: 50.80%	10Li N: 100.00%	11Li 8.59 MS β-: 100.00% -nα: 0.027%	12Li <10 NS N		
	5He 0.60 MeV N: 100.00% α: 100.00%	6He 806.7 MS β-: 100.00%	7He 150 KeV N	8He 119.1 MS β-: 100.00% β-n: 16.00%	9He N: 100.00%	10He 300 KeV N: 100.00%			
1	4H 4.6 MeV N: 100.00%	5H 5.7 MeV N: 100.00%	6H 1.6 MeV N: 100.00%	7H 29E-23 Y 2N?					
	3		5		7		9		11

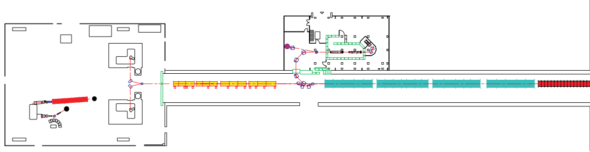


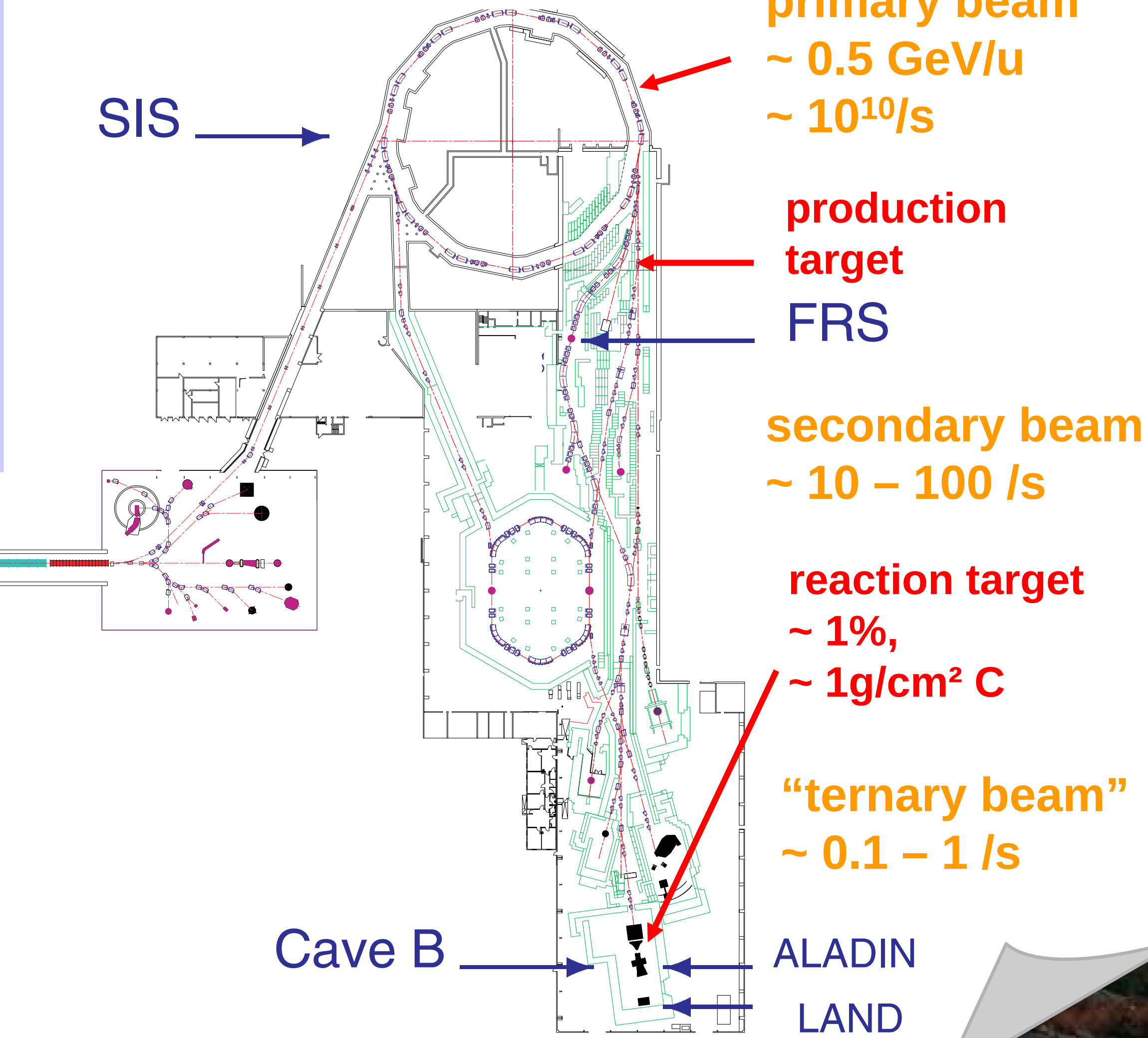
□ unbound

□ beams @ GSI

Typical Intensities @ GSI

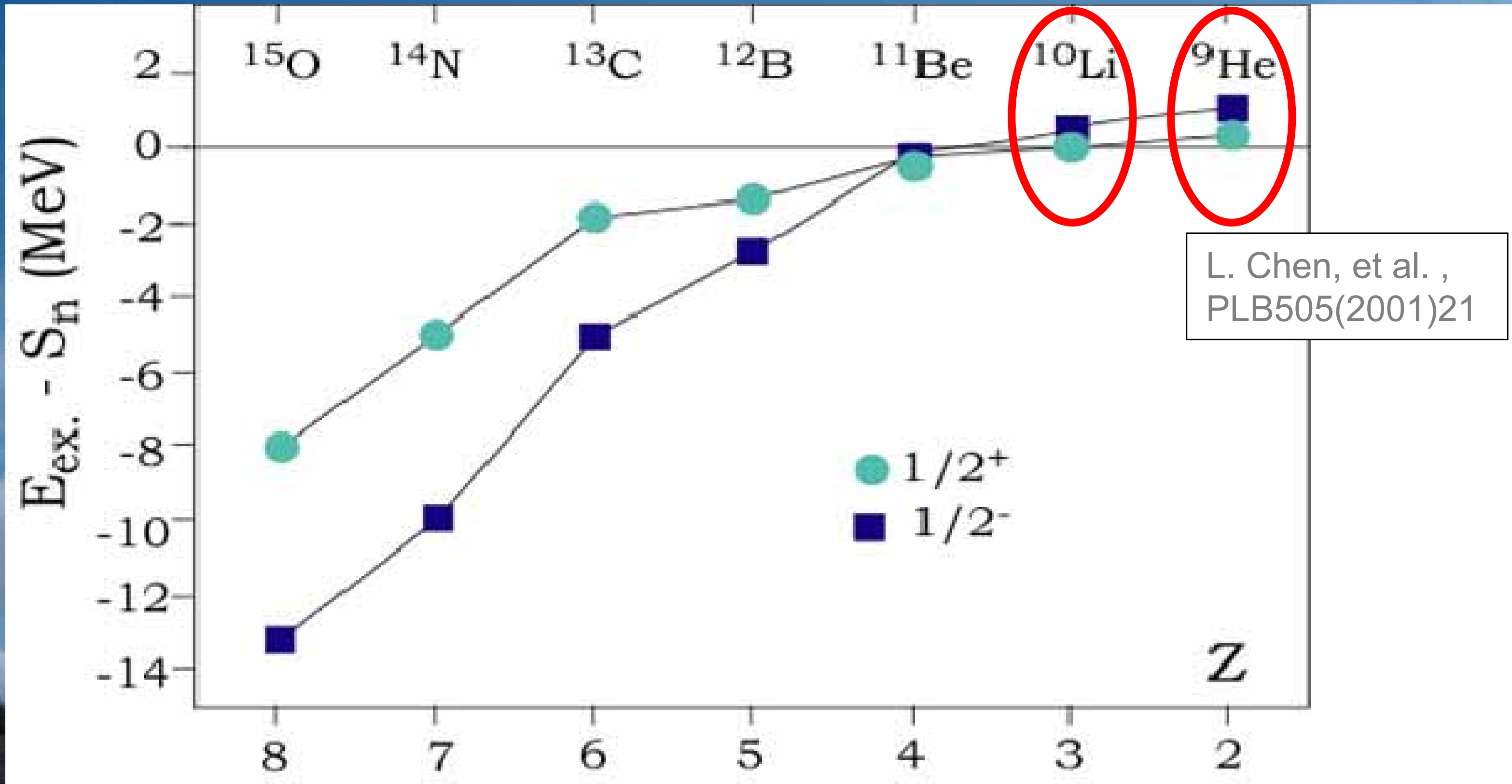






50m

Systematics: intruder states (here N = 7)



L. Chen, et al. ,
PLB505(2001)21

I. Talmi, I. Unna, Phys. Rev. Lett. 4 (1960) 469
P.G. Hansen, Nucl. Phys. A682 (2001) 310c

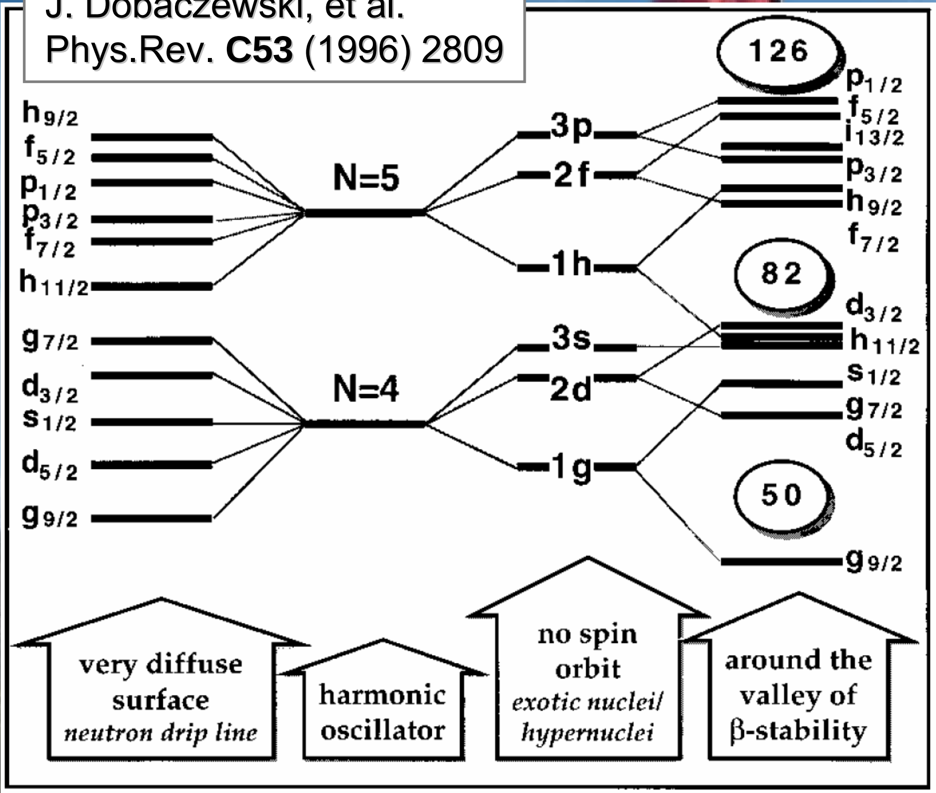
Shell reordering: Halo formation

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

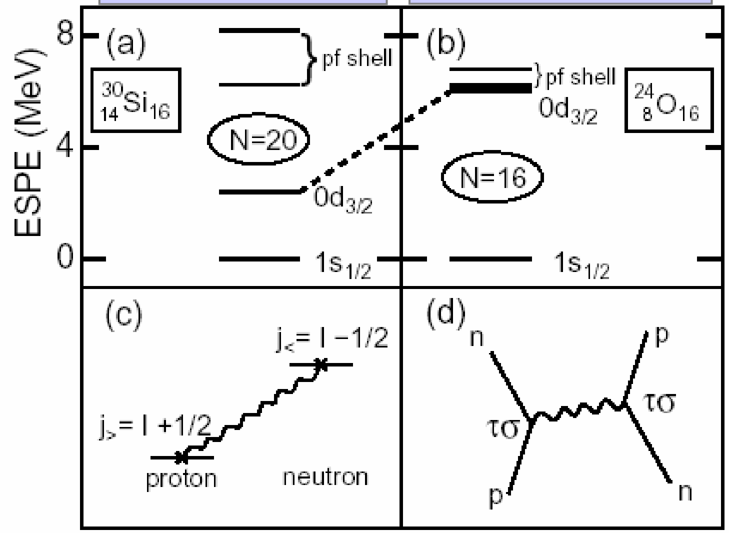
$\sigma\sigma\tau\tau$ interaction :

coupling of p-n spin-orbit partners in partly occupied orbits

→ new magic numbers 6, 16, 34 …

N=20 shell gap vanishes

New shell closure at N=16

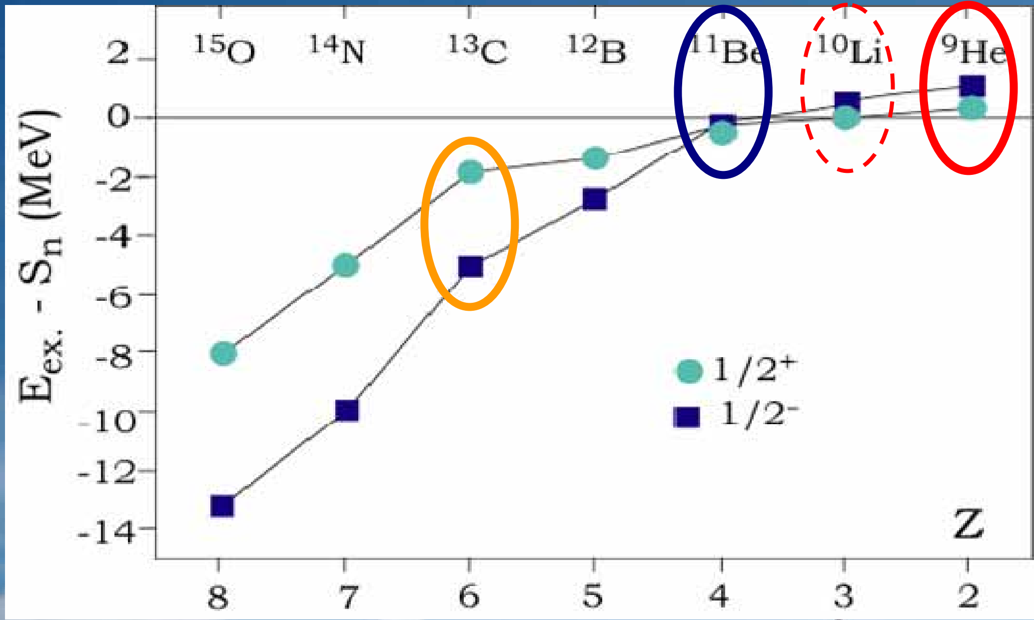


T.Otsuka et al.,Phys.Rev.Lett.**87** (2001) 082502

Z=14 → Z=8: Removing $0d_{5/2}$ protons

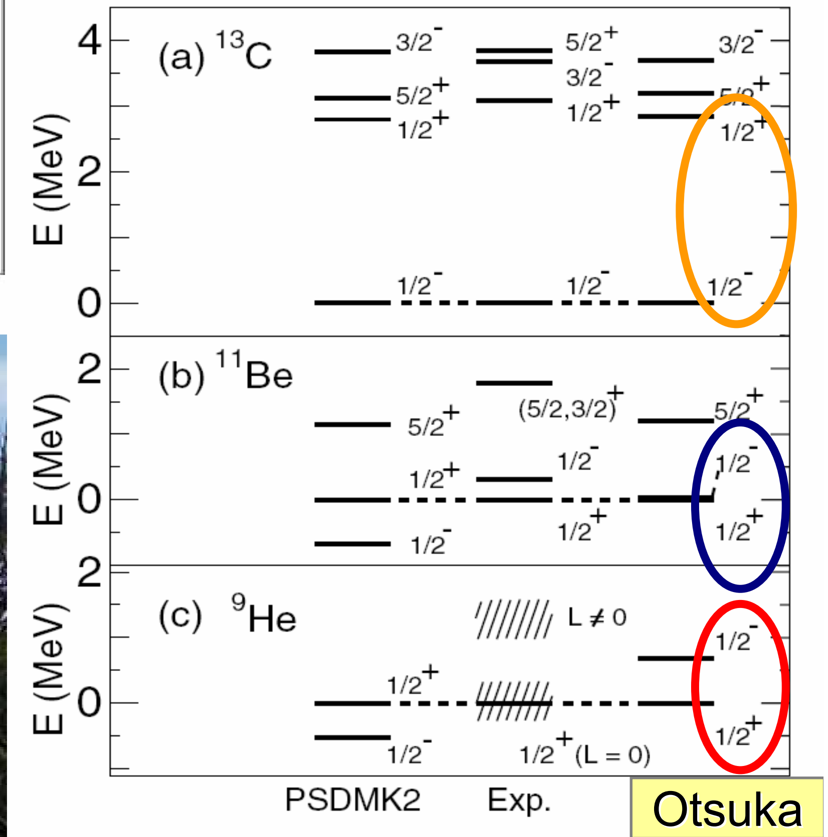
→ less binding for $0d_{3/2}$ neutrons

Otsukas prediction: intruder states

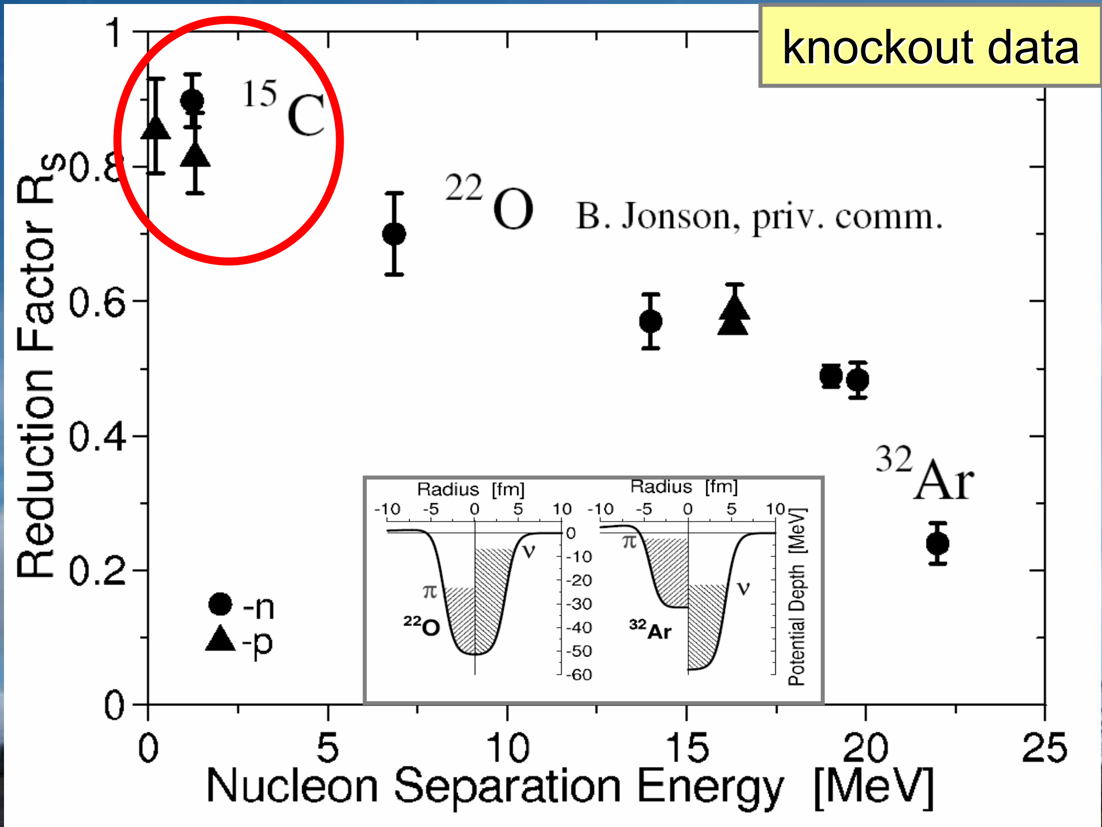


T. Otsuka *et al.* ,
Phys. Rev. Lett. 87 (2001) 082502

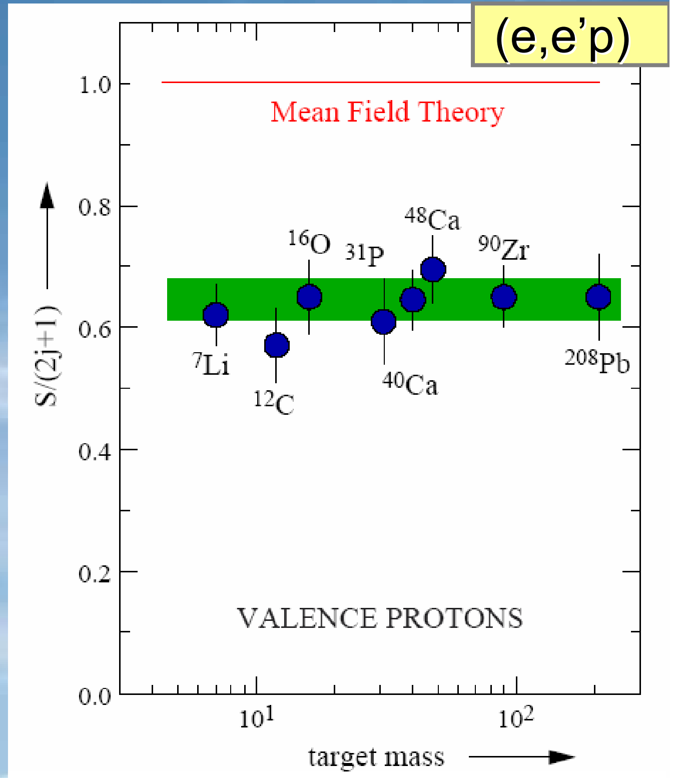
I. Talmi, I. Unna, PRL4 (1960) 469
P.G. Hansen, NUPA682 (2001) 310c



Spectroscopic factors: knockout vs. (e,e'p)



A. Gade et al., Journ. Phys. Conf. **20** (2005) 95



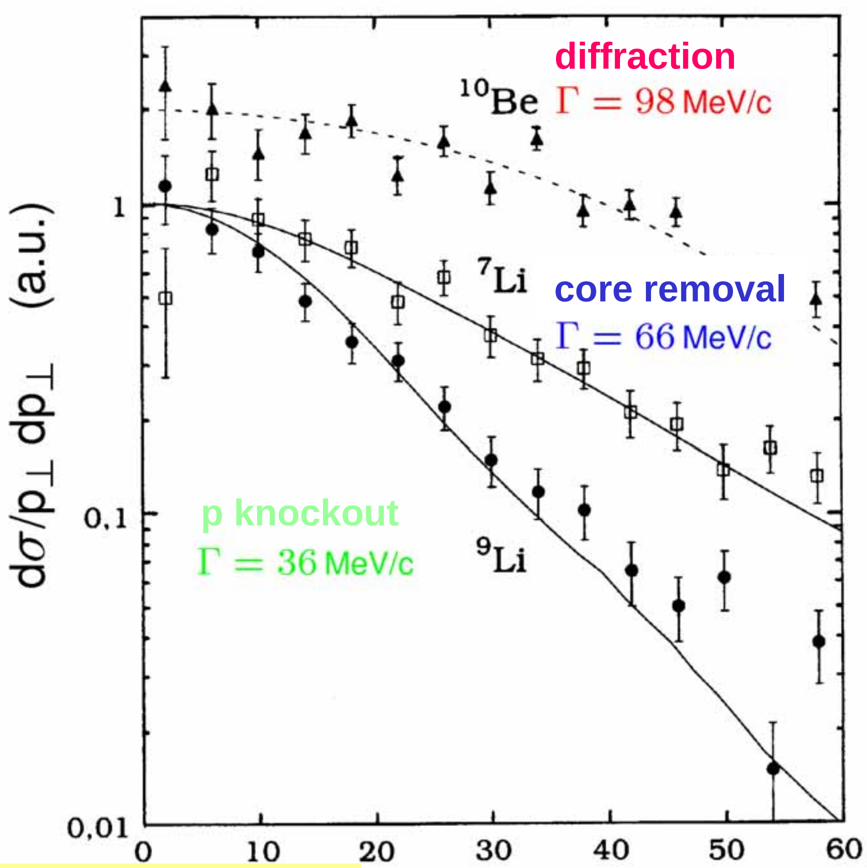
W.H. Dickhoff, C. Barbieri
Prog. Part. Nucl. Phys. **52**
(2004) 377–496

➔ **Dependance on separation energy (difference)** Phys. Rev. C77 (2008) 044306

Starting Point: Neutron Momentum Distributions

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

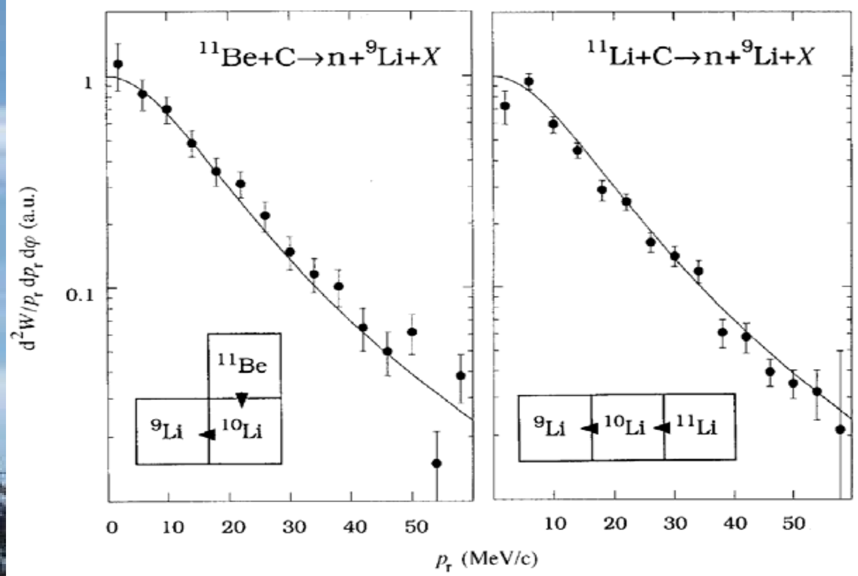
^{11}Be + C $\longrightarrow$ n + ^{Z}A + X



M. Zinser et al.
PRL**75** (1995) 1719

$p_\perp$ (MeV/c)

1n-halo
p/n knockout
2n-halo



B. Jonson, K. Riisager ➔ FSI
Phil. Trans. R. Soc. Lond. A **356** (1998) 2063

➔ reconstruction of the unbound intermediate system necessary !

Experimental approach

Particle continuum spectroscopy
and missing momentum analysis
(at relativistic energies: 0.2-0.3 GeV/u)

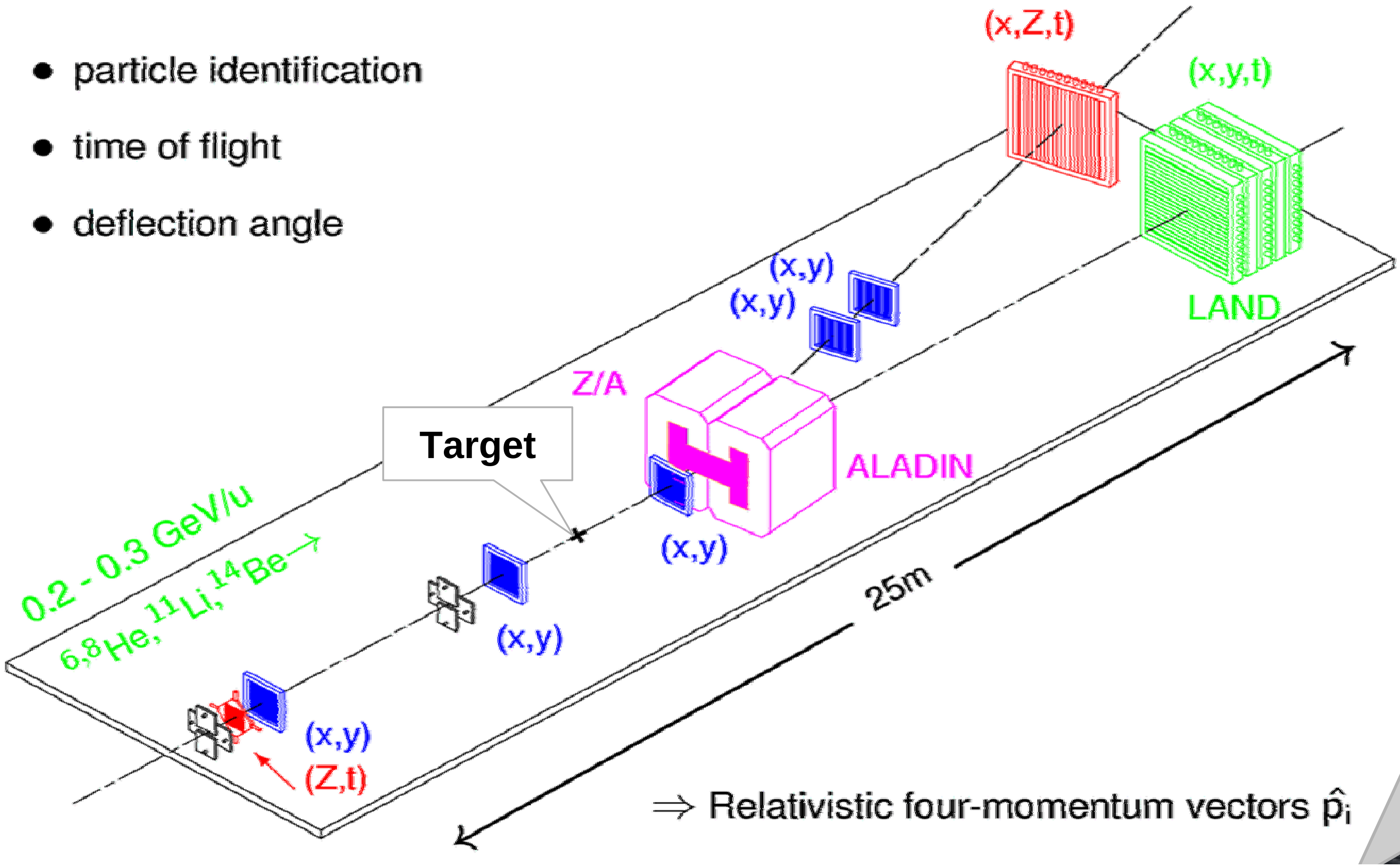
- clean production and detection
- relative energy measurement
- J^{π} assignment

Challenges

- low statistics
- reaction mechanism vs. structure (breakup reactions)
- detection issues

Experimental Setup (kinematically complete)

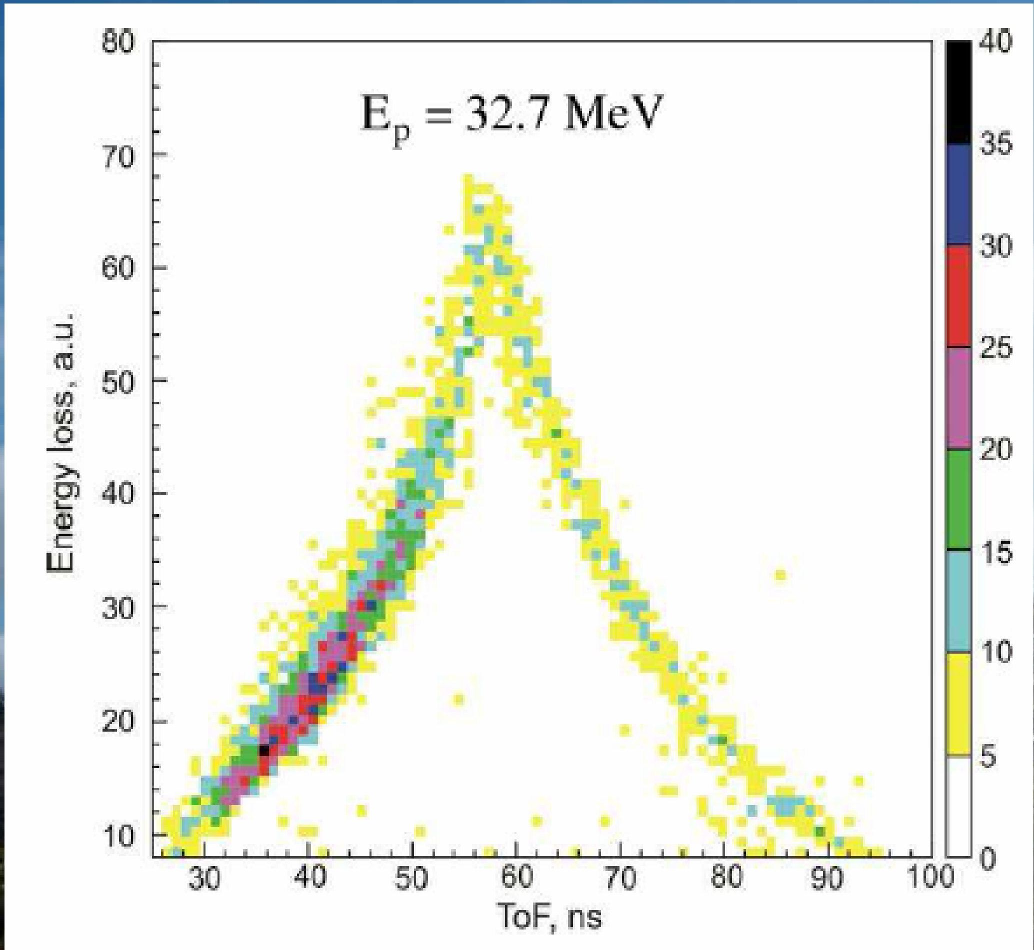
- particle identification
- time of flight
- deflection angle

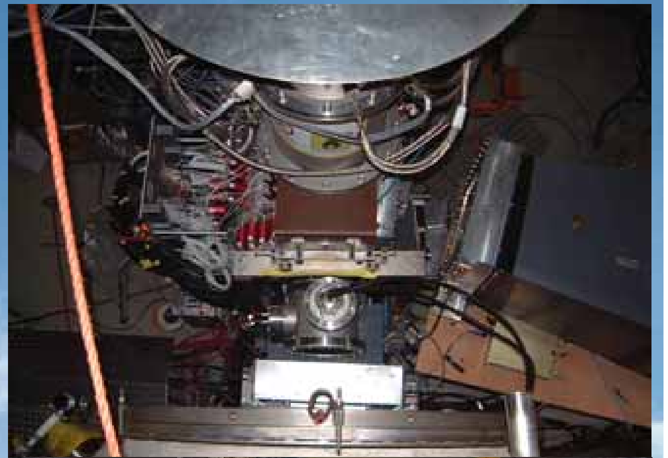


⇒ Relativistic four-momentum vectors $\hat{p}_i$

Experimental Setup (less schematic)

Recoil proton detection !





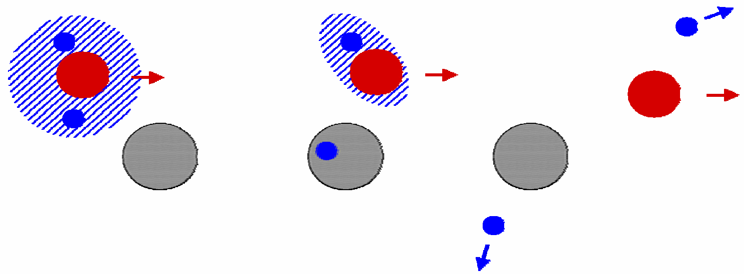
First attempt for an ALADiN/LAND experiment 2001…

Two-body final state from 3-body system (2n-Halo Nucleus)

Toolbox:

Momentum of the knocked out neutron ? (groundstate property)

→ missing momentum



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

Spectroscopy of intermediate system

→ relative energy from relative momentum

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

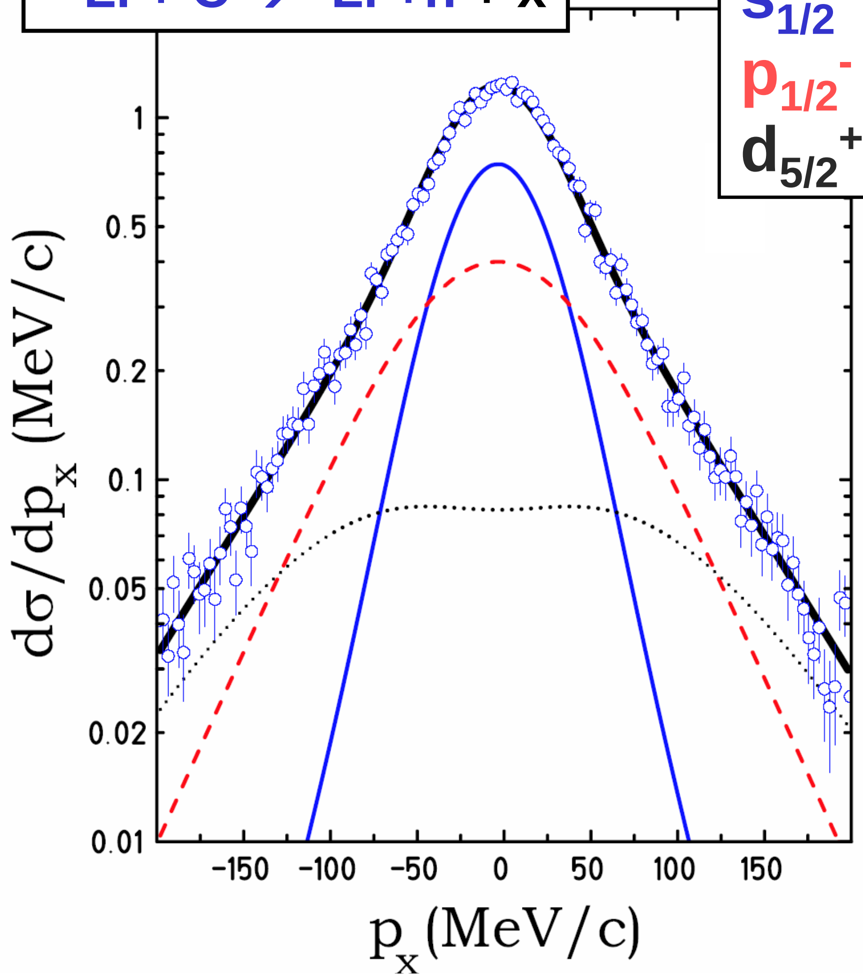
$E_{fn} = p_{fn}^2 / 2\mu$

… or invariant mass via Mandelstam s

^{11}Li : Missing momentum distribution

$p_m = (p_f + p_n)$

^{11}Li + C → ^{9}Li +n + x



$s_{1/2}^{+}$ 41(2)%
$p_{1/2}^{-}$ 42(3)%
$d_{5/2}^{+}$ 17(6)%

H.S. et al., Nucl. Phys. **A 791** (2007) 267

$Y_{lm}(\mathbf{r}) \propto k^{3/2}\, h_l(ikr)\, Y_{lm}(\theta,\phi)$

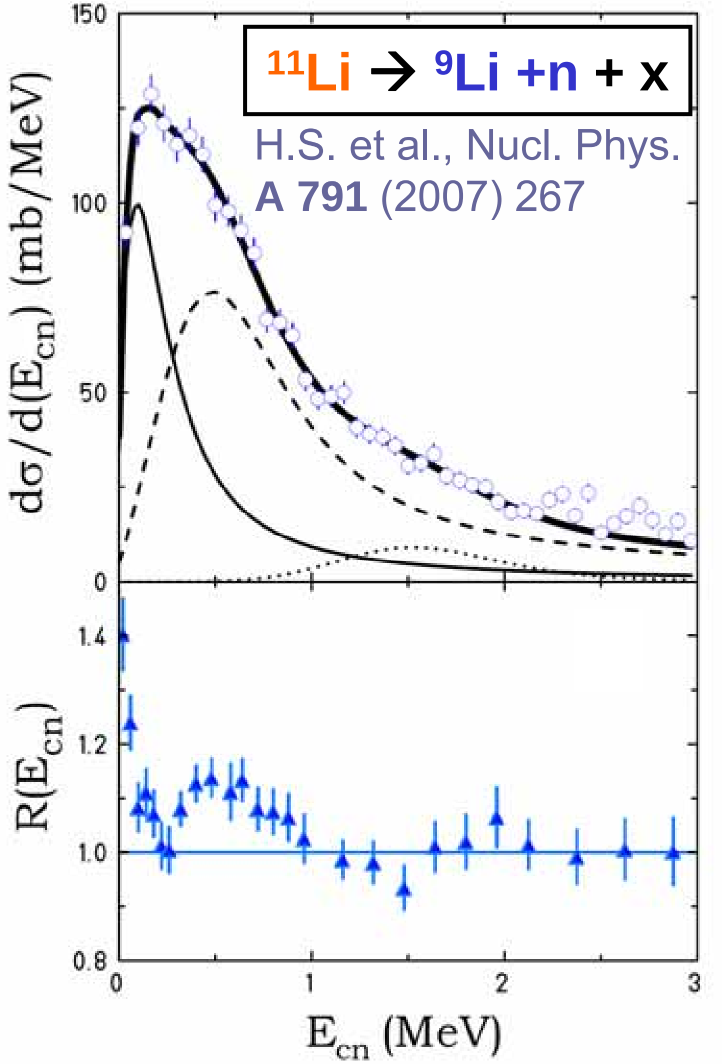
- $k = (2\, \mu\, S_n)^{-1/2}$
  from ^{10}Li relative energy spectrum
- core survival ↔ cylindrical cut

P.G. Hansen Phys.Rev.Lett.**77**(1996)1016

Result: **strong sensitivity / ^{11}Li g.s. configuration**

s, p, (d) components
partial cross sections
spectroscopic factors

^{11}Li → ^{10}Li: Relative energy spectrum



- steep rise at threshold → ℓ = 0

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

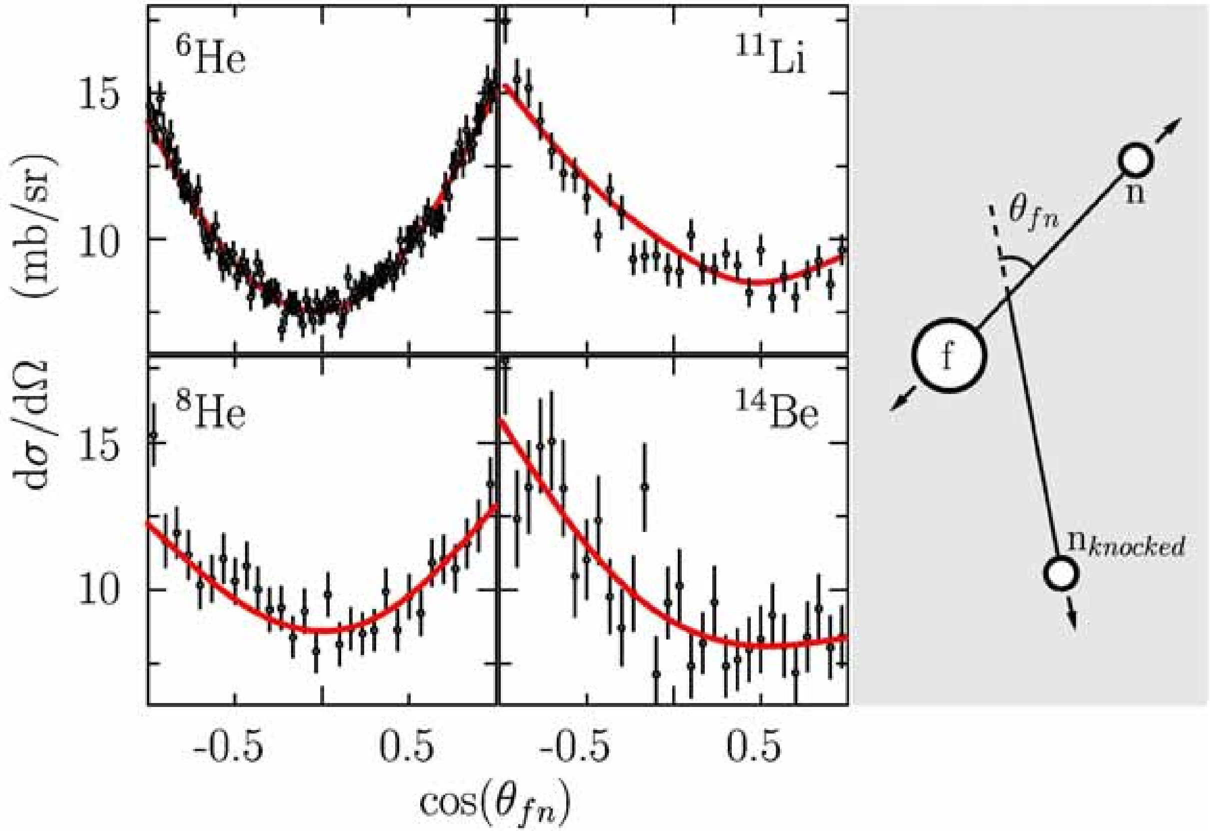
- confirmed by ang. correlations
  (−22.4(4.8) fm / 0.566(14) MeV IH_2 target)
- correlated events ?

R = dσ/dE / dσ/dE$_{mix}$

- spin assignment ?

2n-Halo : n-n angular correlations

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



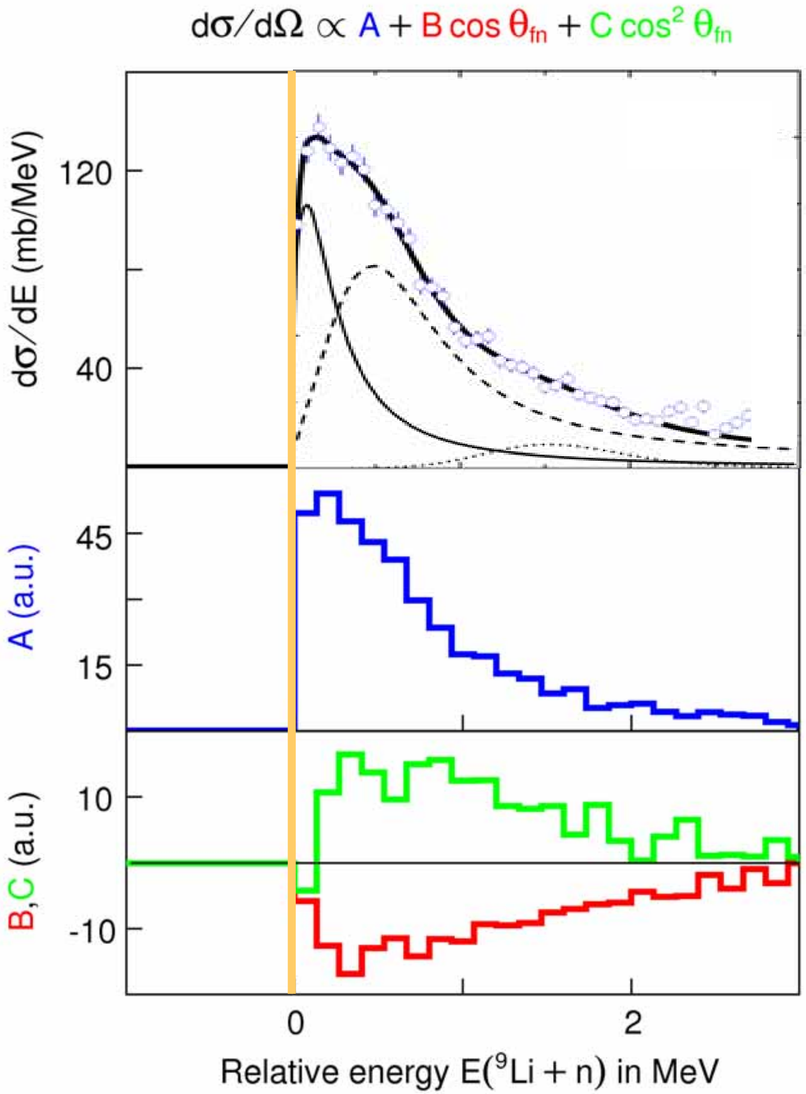
Angular correlations:

- peripheral reaction → alignment
- intermediate unbound systems have lifetimes of a few 100fm/c

L.V. Chulkov et al., Phys Rev. Lett. **79**(1997)201

- momentum transfer small
- interferring states of different parity

^{11}Li →^{10}Li: combining bits and pieces



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

Conclusion: ^{10}Li

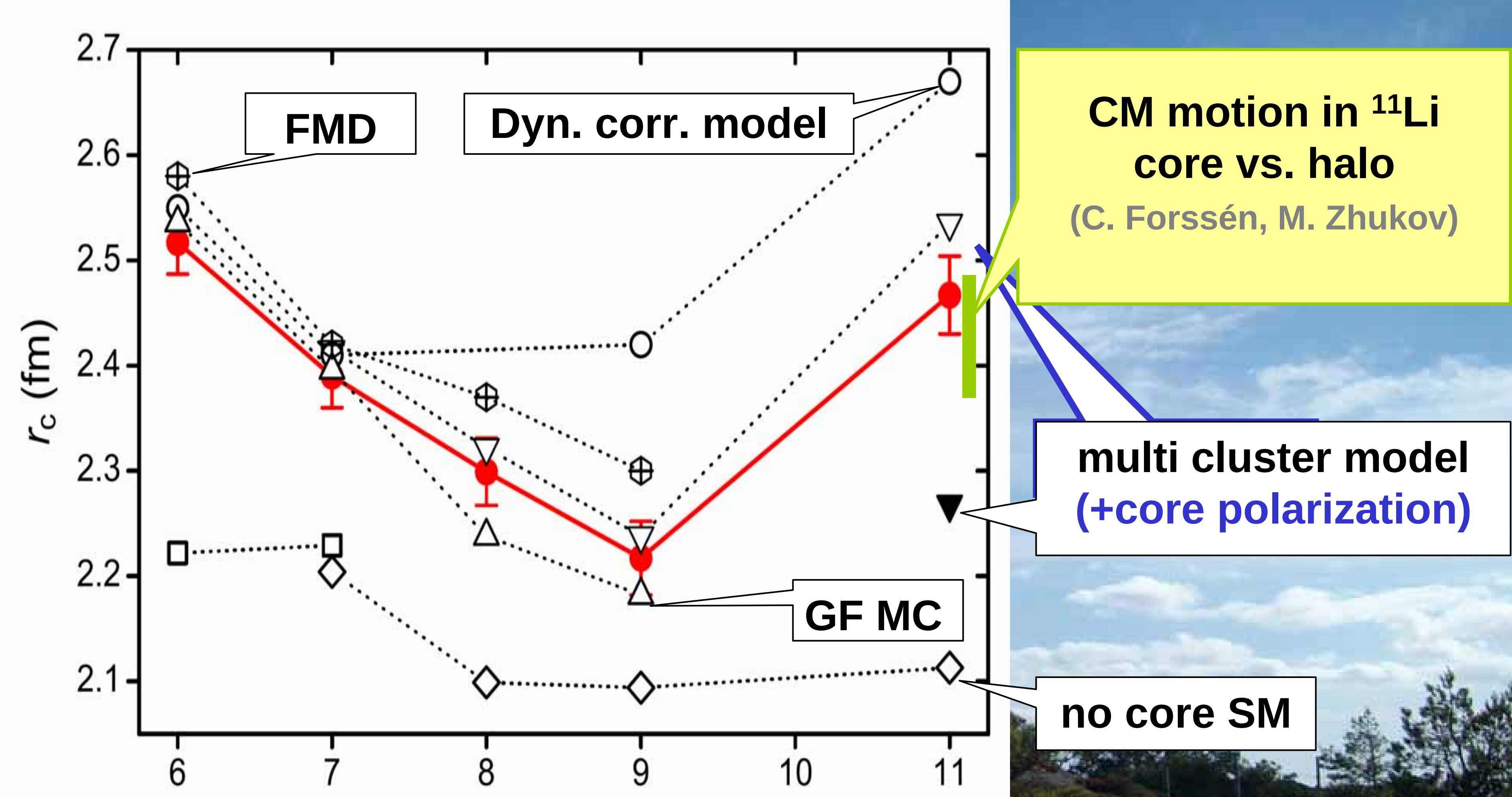
consistent description of observed

1. momentum distribution
   →angular momenta
2. energy spectra
   → position states
3. angular correlations
   → sequence of states

➔ e.g. Garrido/Fedorov/Jensen NUP**A700**(2002)117

Application

LASER spectroscopy: charge radii Li isotopes



R. Sanchez, et al.
Phys. Rev. Lett. 96 (2006) 033002

!

To calculate the charge radii of ^6He or ^{11}Li we need to know the charge radii of the cores ^4He and ^9Li (r_{ch}) and the distances of the cores (ΔR_c) from the center of mass of the corresponding nuclei (^6He, ^{11}Li)

$$r_{ch}(core+2n) = [r_{ch}^2(core) + (\Delta R_c)^2]^{1/2}$$

(^6He) $r_{ch}(^4He) = 1.673$ (known for many years back)

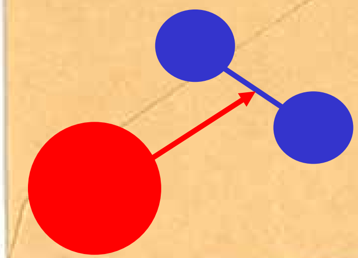
$\Delta R_c(^4He)$ we can take from exp. paper [T. Aumann.., PRC 59 (1999) 1252] where this number has been obtained from cluster non energy weighted sum rule $S_{clus.}^{NEW} = \frac{3}{4\pi} Z_c^2 e^2 (\Delta R_c(^4He))^2 \leftrightarrow \Delta R_c^{exp}(^4He) = 1.12 \pm 0.13$ or theor. calculations [B.V. Danilin... NPA 632 (1998) 383] $\leftrightarrow \Delta R_c^{th}(^4He) = 1.2$

$r_{ch}^{exp}(^6He) = 1.944 \div 2.088$ fm $\qquad r_{ch}^{th}(^6He) = 2.059$ fm

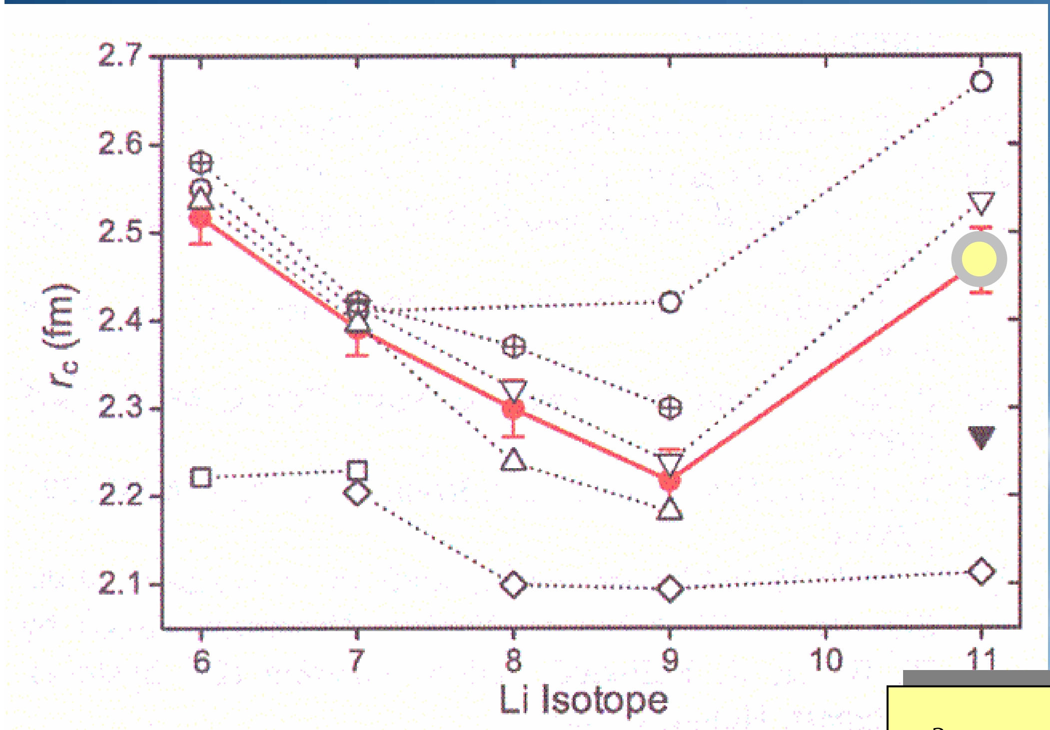
(^{11}Li) $r_{ch}(^9Li) = 2.24 \pm 0.04$ [G. Ewald.., PRL 94 (2005) 039901]

$\Delta R_c(^9Li)$ is not known experimentally. From theor. paper [Ch. Forssen ... NPA (2002) 48] we can get two values: $\Delta R_c^{th}(^9Li) = 1.08$ or $\Delta R_c^{th}(^9Li) = 0.8$, depending on correlations in ^{11}Li WF (unknown from exp.)

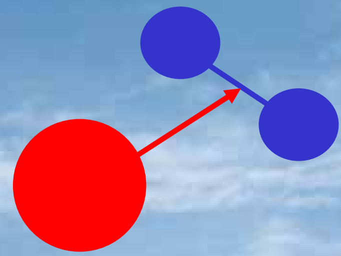
$r_{ch}^{th}(^{11}Li) = 2.49 \pm ...$ fm or $r_{ch}^{th}(^{11}Li) = 2.38 \pm ...$ fm



^{11}Li: core stays (most probably) inert !



cos(θ_{fn}) from exp. !
H.S. et al. PRL **83** (1999) 496



$$R^2_{cm} = \frac{2}{99} < \rho^2 >< \cos^2 \theta >$$

with $< \rho^2 >= 90\ fm^2$, $< \cos^2 \theta >= 0.6466$

and $R_{ch}(9Li) = 2.217\ fm$ fixed from the experiment

$$R_{ch}(11Li) = \sqrt{R^2_{cm} + R^2_{ch}(9Li)} = 2.468\ fm$$

$$R_{ch}(\exp) = 2.467(37)$$

M.V. Zhukov
N. Shulgina
C. Forssén

^{11}Li: Mass, magnetic moment !

N. Shulgina et al. to be published

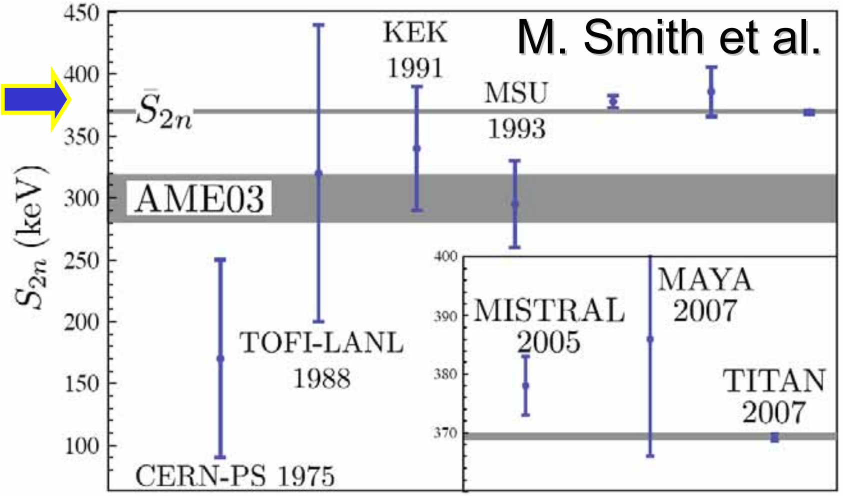
- halo neutrons coupled to J=0(94%),J=1,2(6%) just 3 harmonics K=0,2

```
T: K=2 lx,ly=1,1 S=1
                0,0    0
T: K=0          0,0    0
```

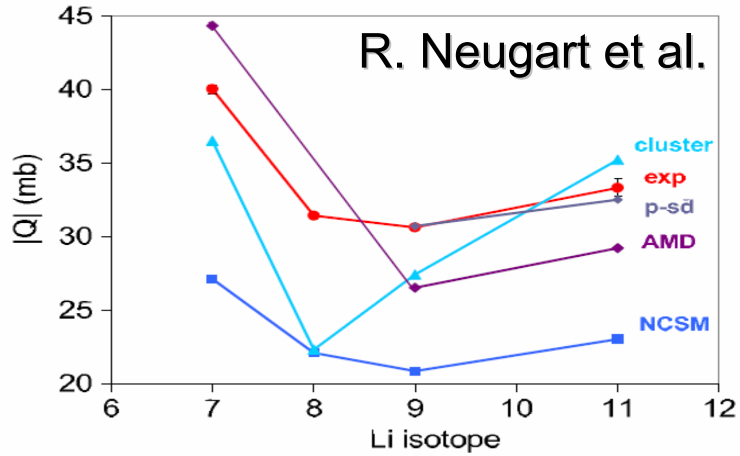
- core inert !
- trying to describe existing data ! radius, binding energy and quadrupole moment, **using correlations**

Result (consistent description):

- binding energy 376 keV (369.15(65) keV)
- charge radius 2.42 fm (2.46(4) fm)
- quadrupole moment 32.8(4) mb (33.3 (5) mb)



PRL **101,** 132502 (2008) PHYSICAL



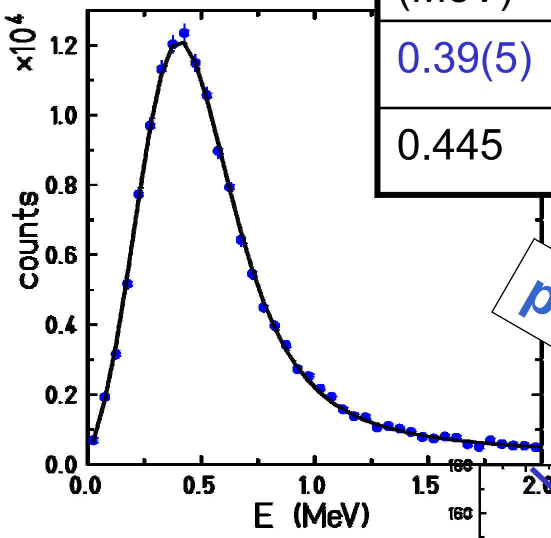
Unbound Helium isotopes: ^{7}He target dependence

$^8He + p \rightarrow {}^6He + n + X$

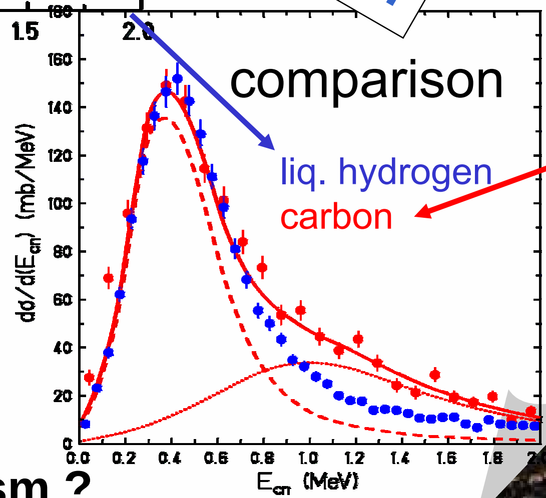
E* (MeV)	Γ (MeV)	Ref.
0.39(5)	0.14(5)	this
0.445	0.15	[1]

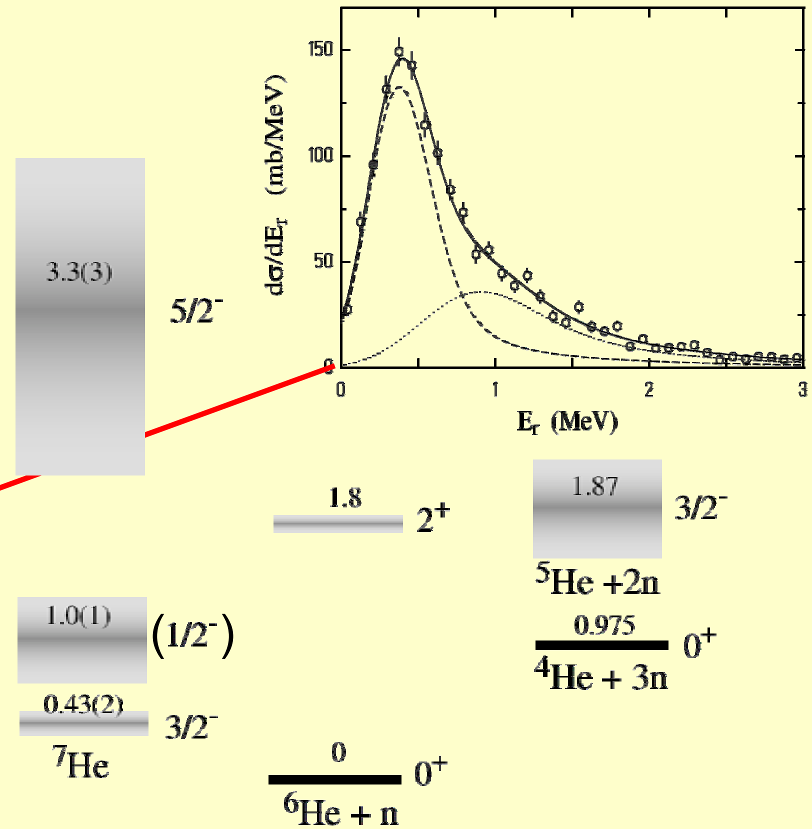
[1] Ajzenberg-Selove

M. Meister et al, PRL **88** (2002) 102501 „Evidence for a New Low-Lying Resonance State in ^{7}He"



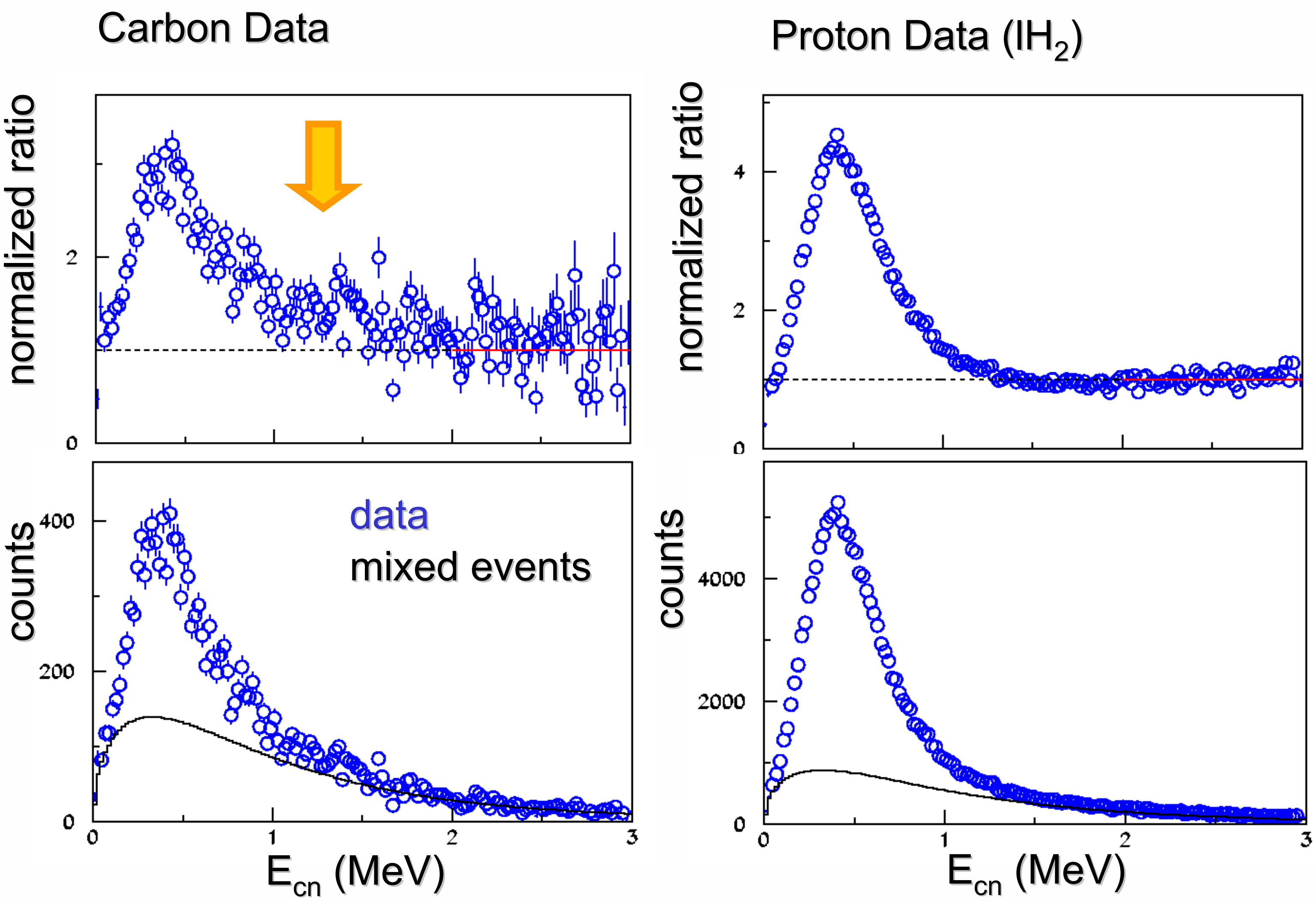
preliminary !





structure ?
reaction mechanism ?

Unbound Helium isotopes: ^{7}He target dependence



➔ correlated events around E_{cn} =1 MeV for both targets

➔ shapes differ !

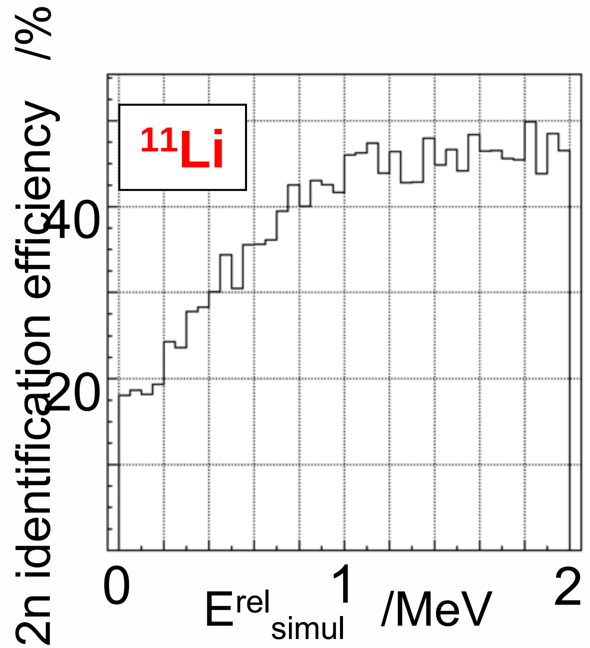
➔ **interpretation ?**

Three-body Continuum Spectroscopy: prerequisites

Nucl. Instr. Meth. A314 (1992) 136

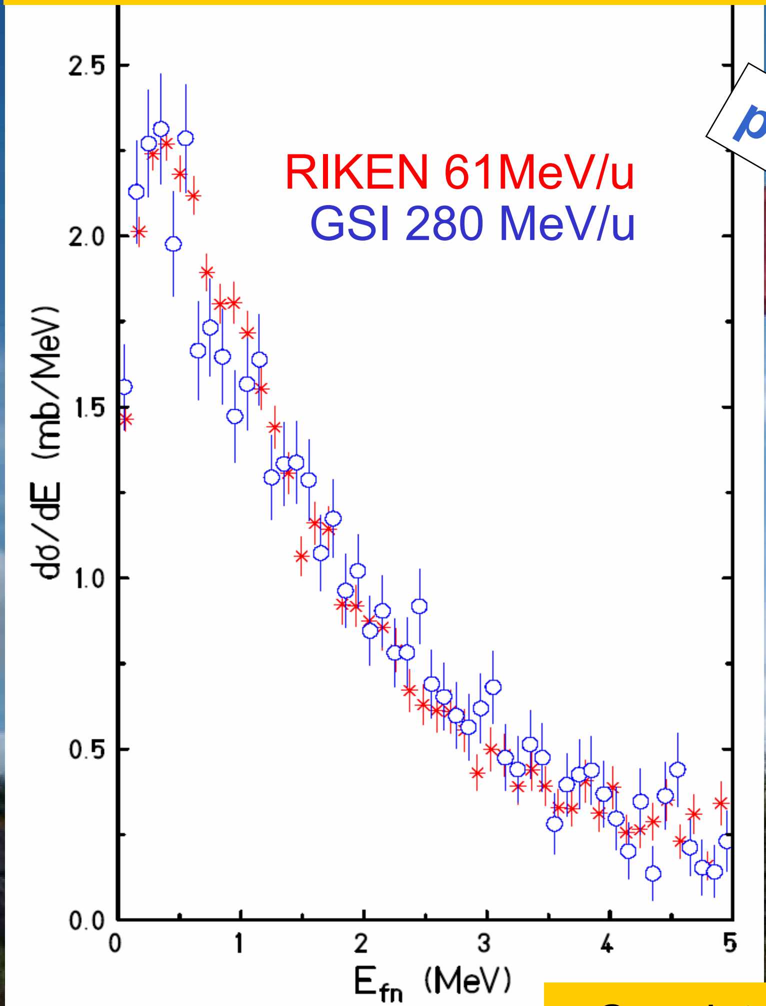
➔ **compute relative energy of all particles emerging from target**

- **large detection efficiency (charged particles, neutrons)**
- **sufficiently high resolution**

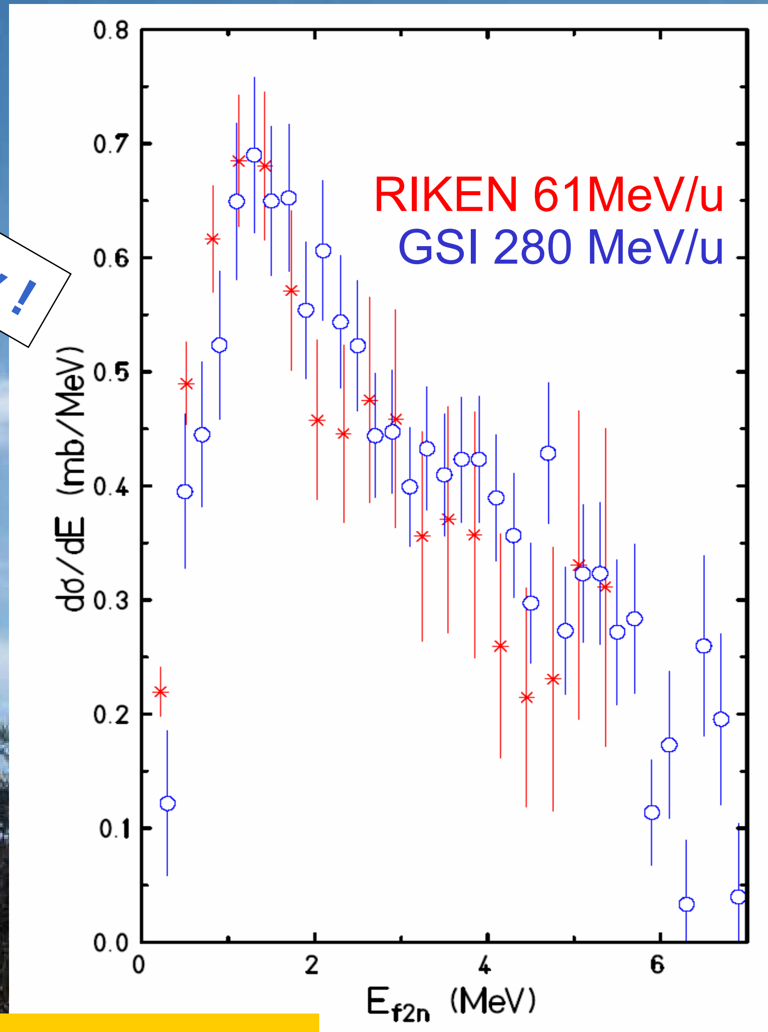


Unbound Helium isotopes: $^{9,10}He$

$^{9,10}He$: ^{11}Li + p/CD_2,C → ^{8}He + n + X



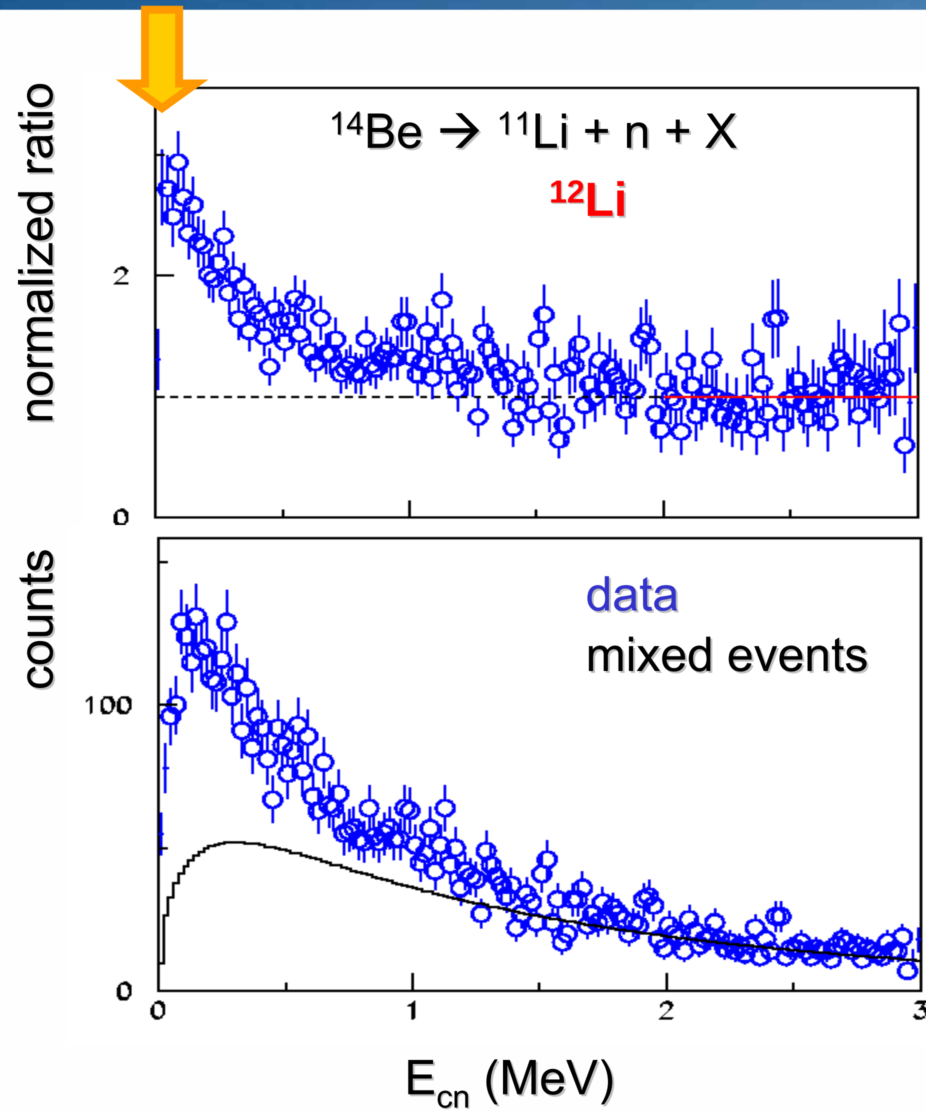
preliminary !



A. Korsheninnikov et al., Phys. Lett. **B326** (1994) 31

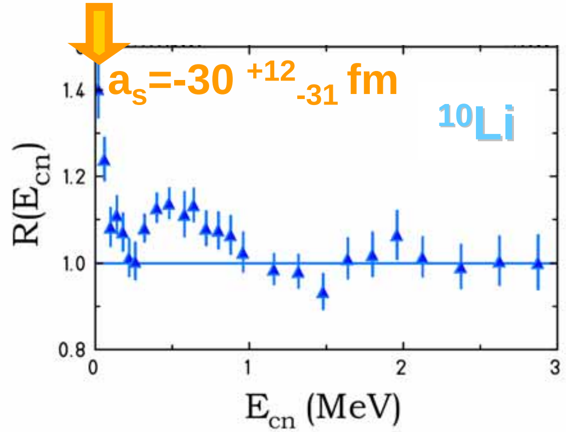
- Consistent with old data set
- Weak ^{11}Li beam (background !)

Unbound Lithium isotopes: ^{12}Li



➔ strongly correlated events !

➔ no two components as in ^{10}Li



➔steep rise at treshold

➔ **virtual scattering state**

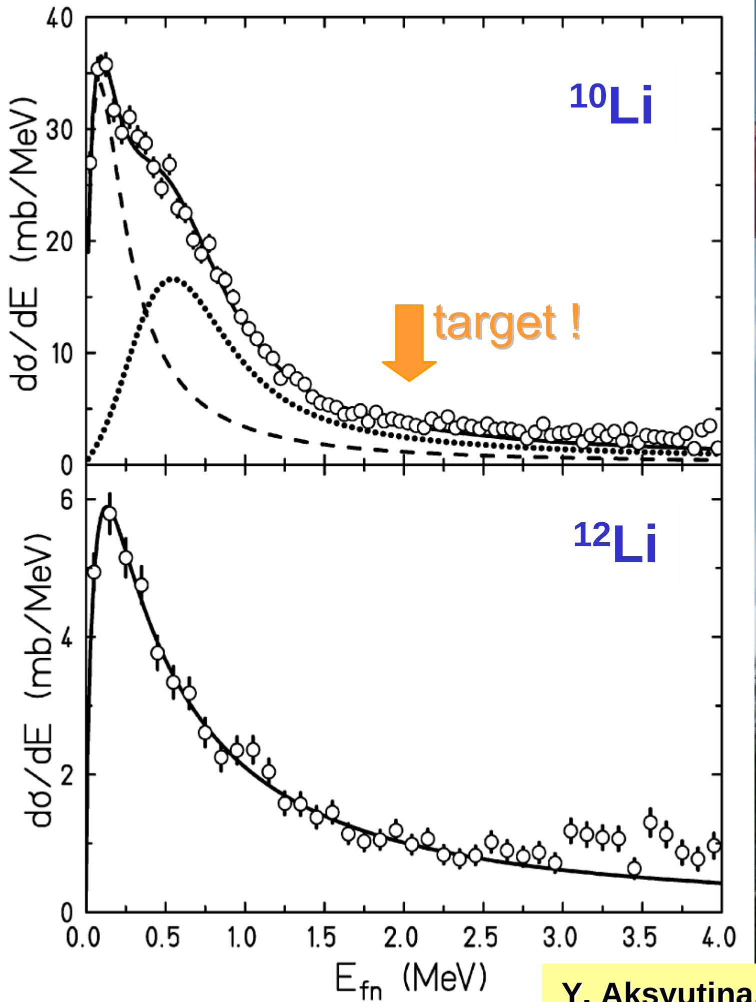
Unbound Lithium isotopes

^{12}Li: ^{14}Be + p → ^{11}Li + n + X

Bertsch, Hencken, Esbensen
PRC57(1998)1366

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

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



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)

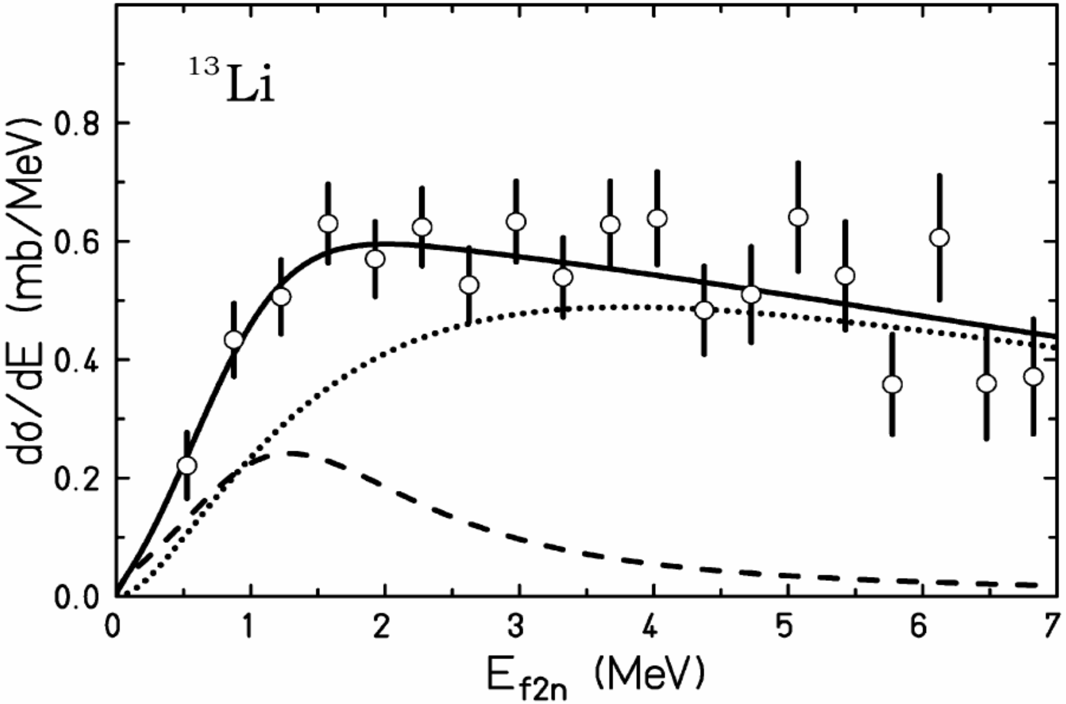
Close to
S_{2n} ^{14}Be

Y. Aksyutina, H. Johansson et al., Phys. Lett. B666 (2008) 430

Unbound Lithium isotopes

^{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

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

➔ ^{11}Li + 2n resonance picture

Evidence for existence
at 1.47(31) MeV

Y. Aksyutina, H. Johansson et al., Phys. Lett. B666 (2008) 430

Summary

- Consistent interpretation for the ^{11}Li halo nucleus via ^{10}Li intermediate system (cross link to other fields)
  → does not mean there's no debate

full tool box available → correlations !

- Heavy He isotope sequence studied
  → interpretation (see next talk)

Physics Letters B 666 (2008) 430–434
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PHYSICS LETTERS B

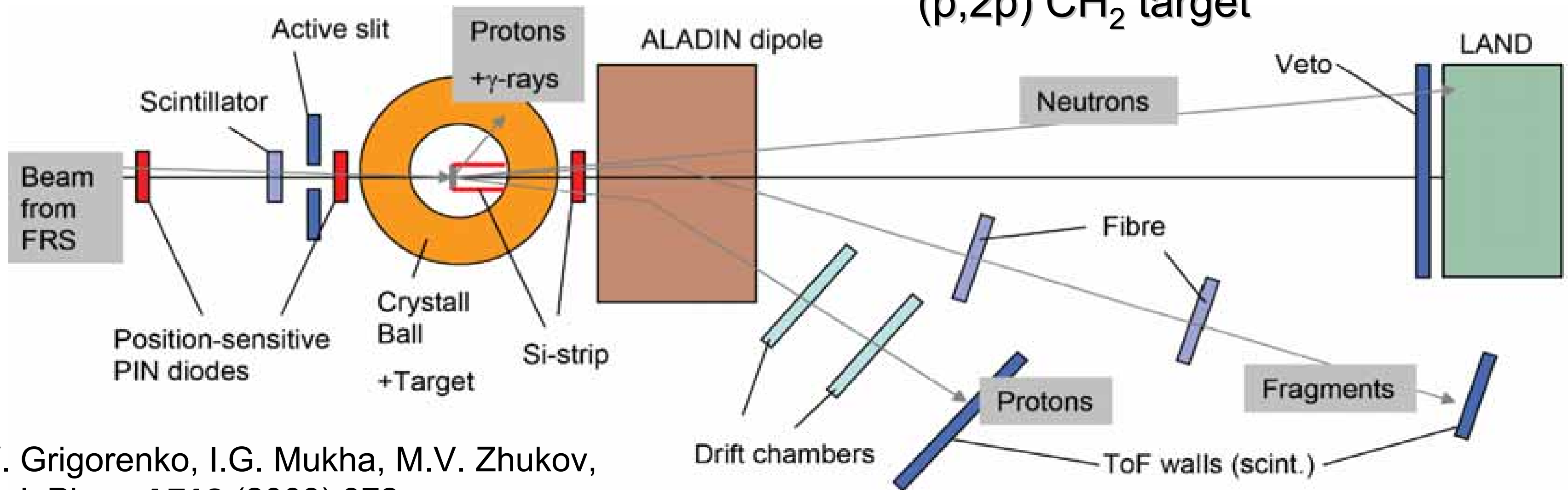
- (Super) Heavy Li isotope sequence studied
  → ^{12,13}Li observed for the first time

At the horizon: R³B, EXL, ELISe /NUSTAR /FAIR

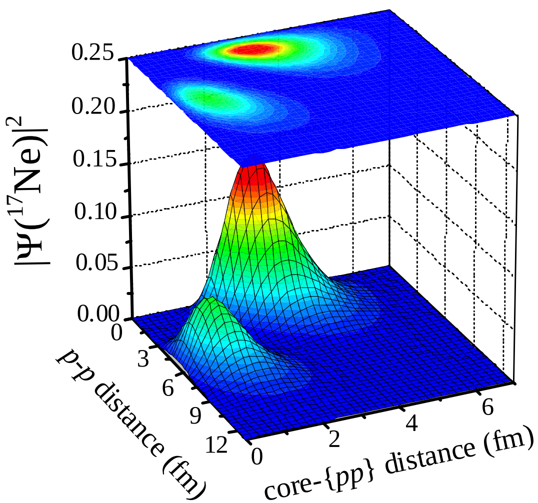
New Experiments (Aug2007 ^{17}Ne, Sep/Oct 2007 ^{12}C QFS, ...)

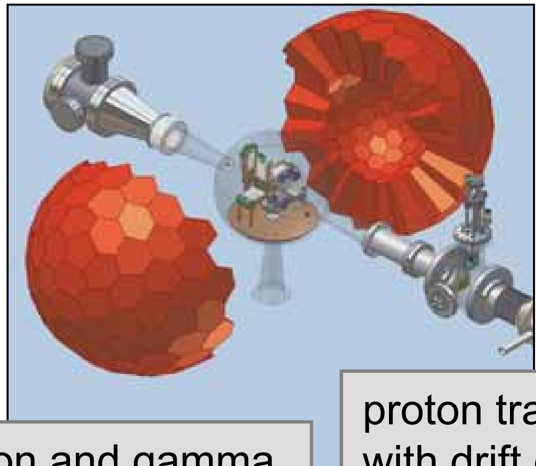
R³B precursor: Setup at Cave C

(p,2p) CH_2 target

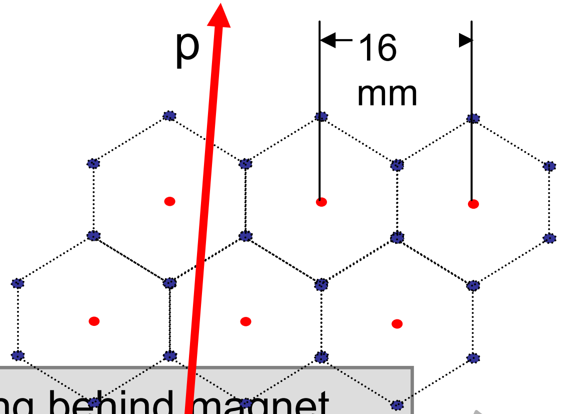


L.V. Grigorenko, I.G. Mukha, M.V. Zhukov, Nucl. Phys. **A713** (2003) 372





proton and gamma detection



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

The S135/S245 collaboration

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Experimental Setup (less schematic, today)