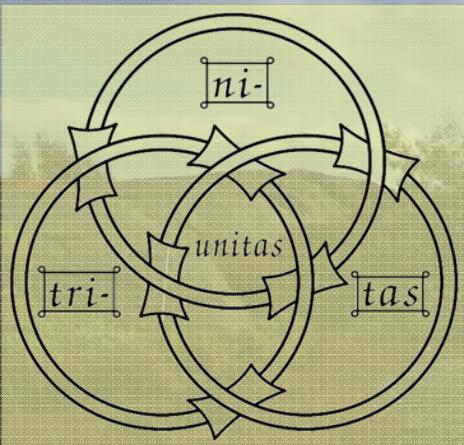


Studies along the dripline at relativistic beam velocities

Haik Simon • Gesellschaft für Schwerionenforschung / Darmstadt

Outline

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

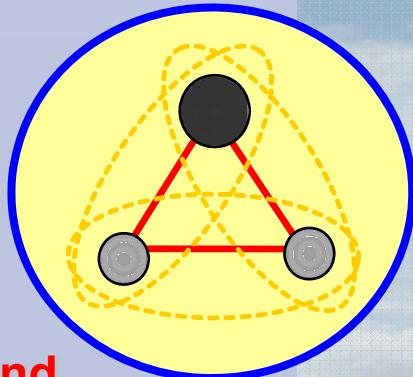


Light ions: the lower part of the chart of nuclei

<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-ns: 1.00%	13Be 2.7E-21 S N	14Be 4.35 MS β-: 100.00% β-n: 81.00%	15Be <200 NS N
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% β-ns: 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%			
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?					

- unbound
- beams @ GSI



3

1

3

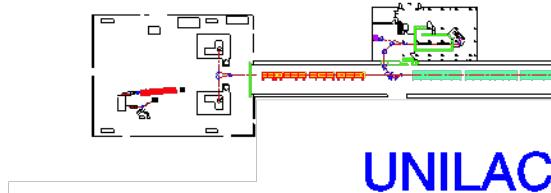
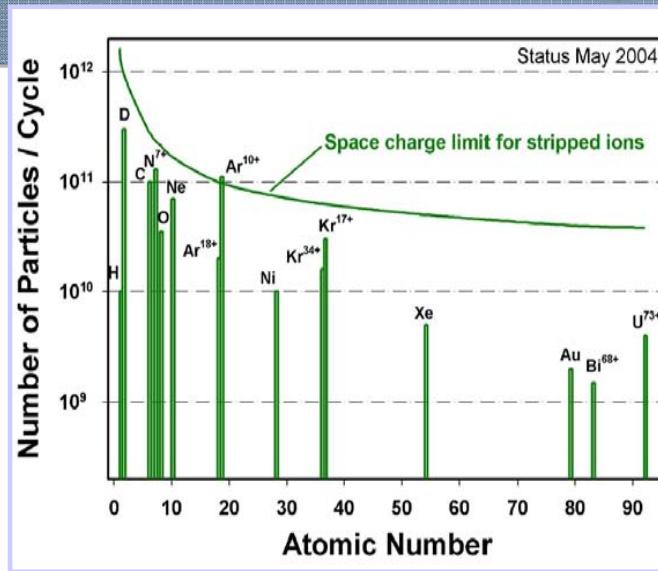
5

7

9

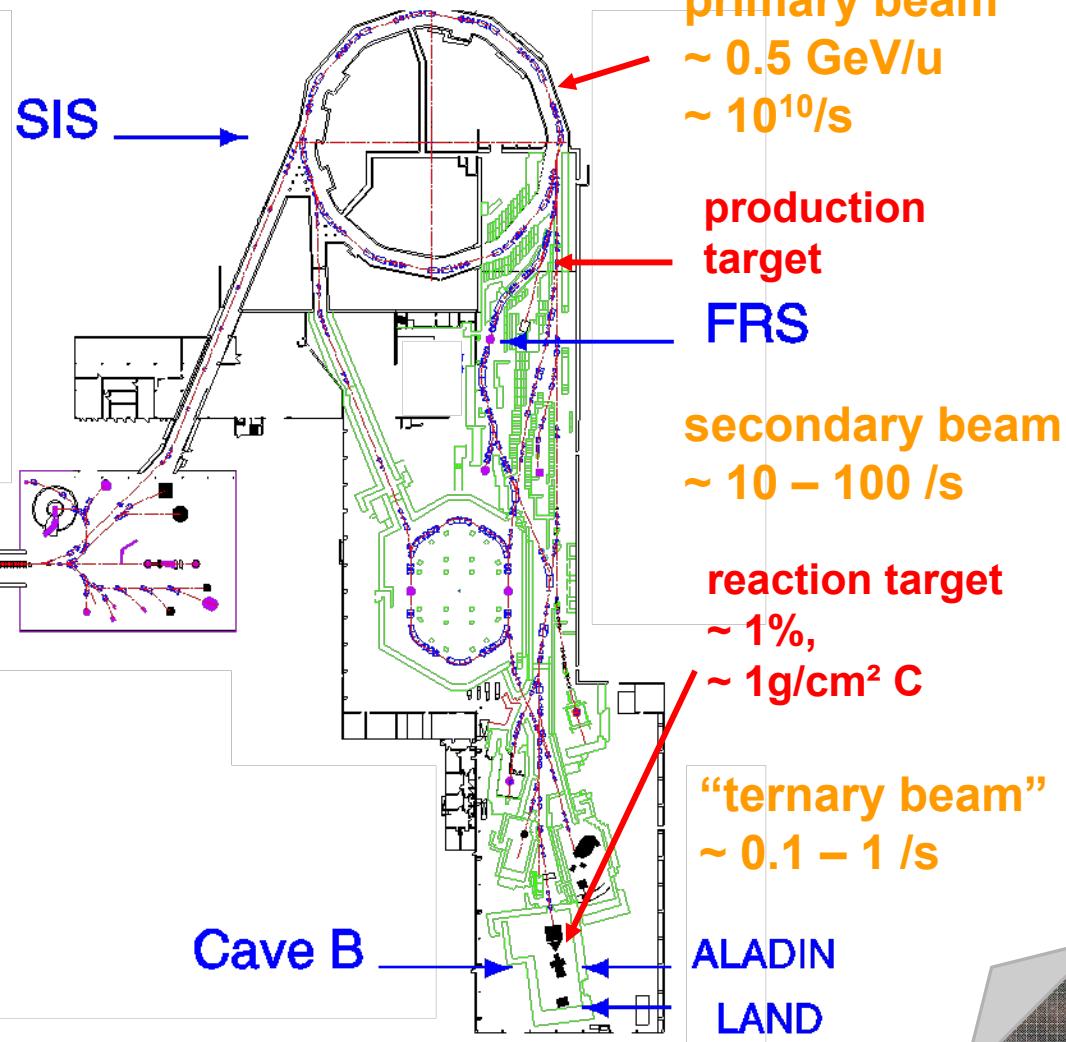
11

Typical Intensities @ GSI

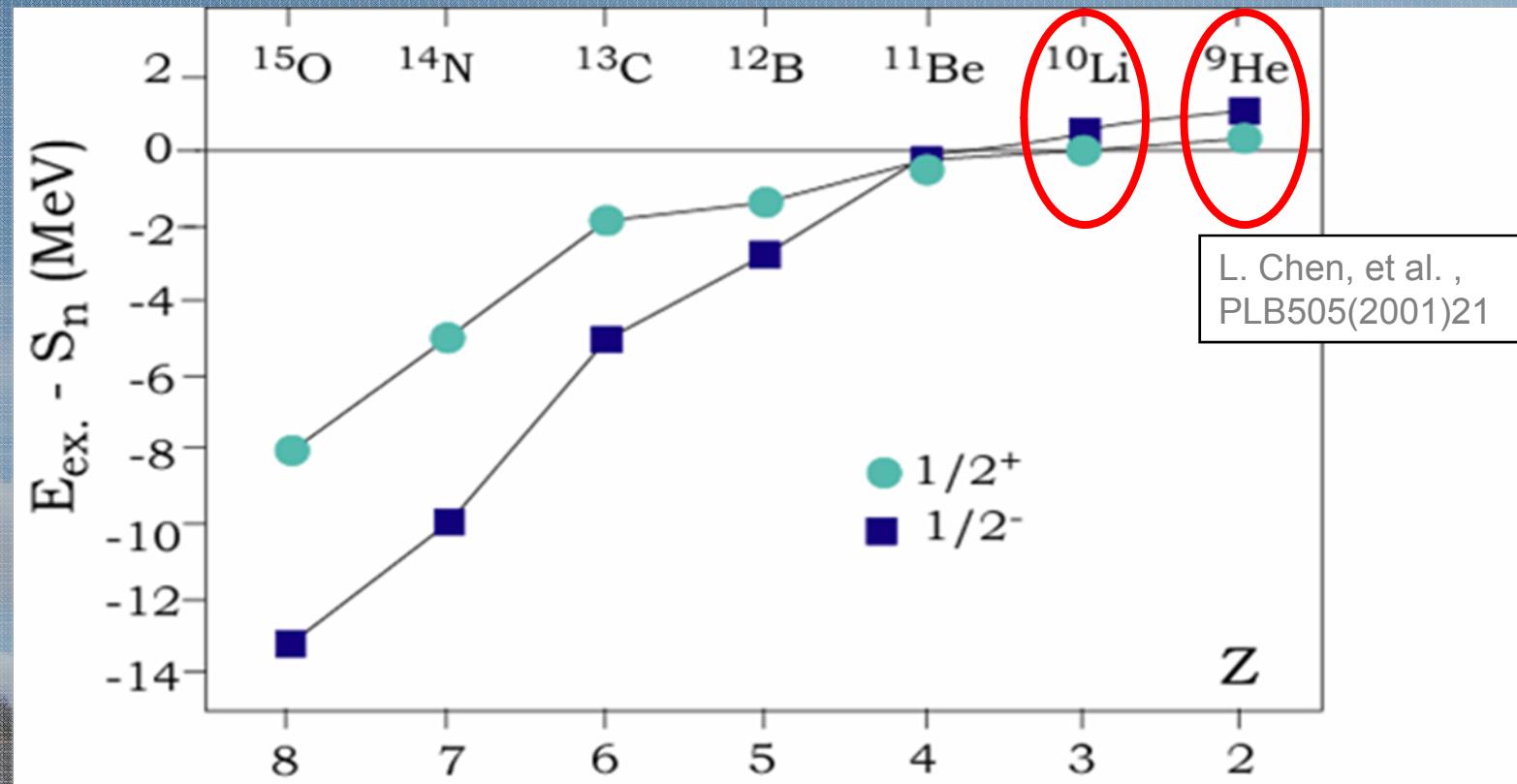


UNILAC

50m



Systematics: intruder states (here N = 7)



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

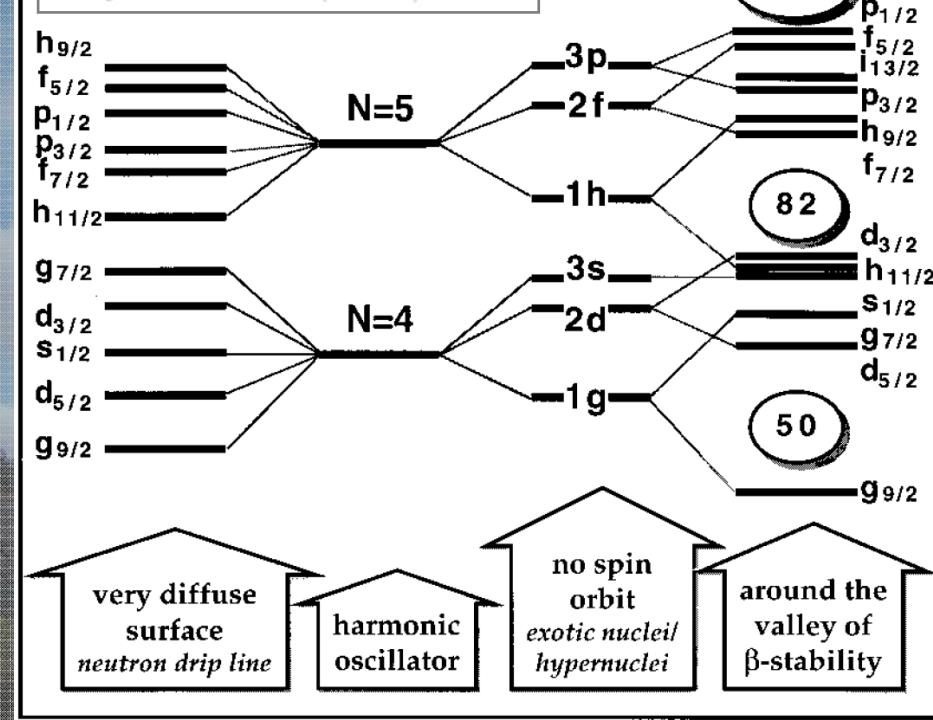
Shell reordering: Halo formation

Mean-field modifications

surface composed of diffuse neutron matter

derivative of mean field potential weaker and spin-orbit interaction reduced

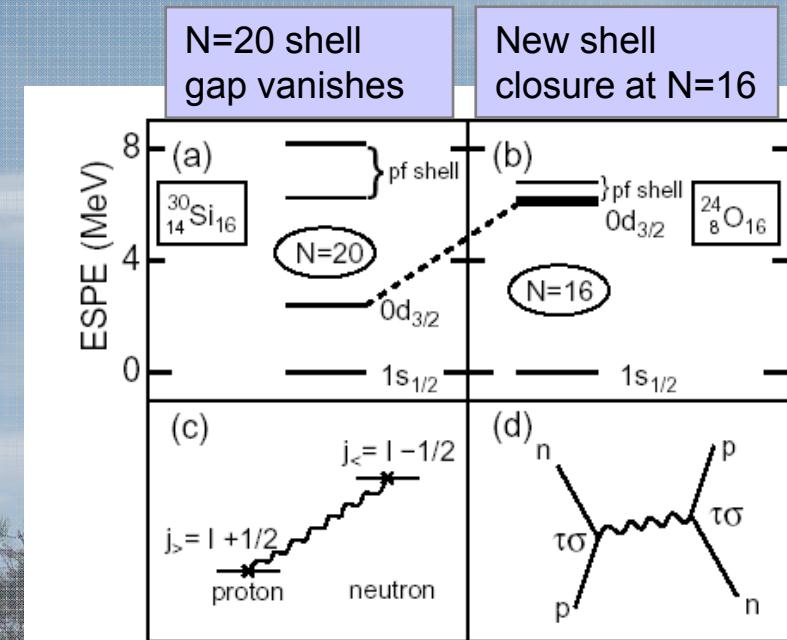
J. Dobaczewski, et al.
Phys. Rev. C53 (1996) 2809



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 ...

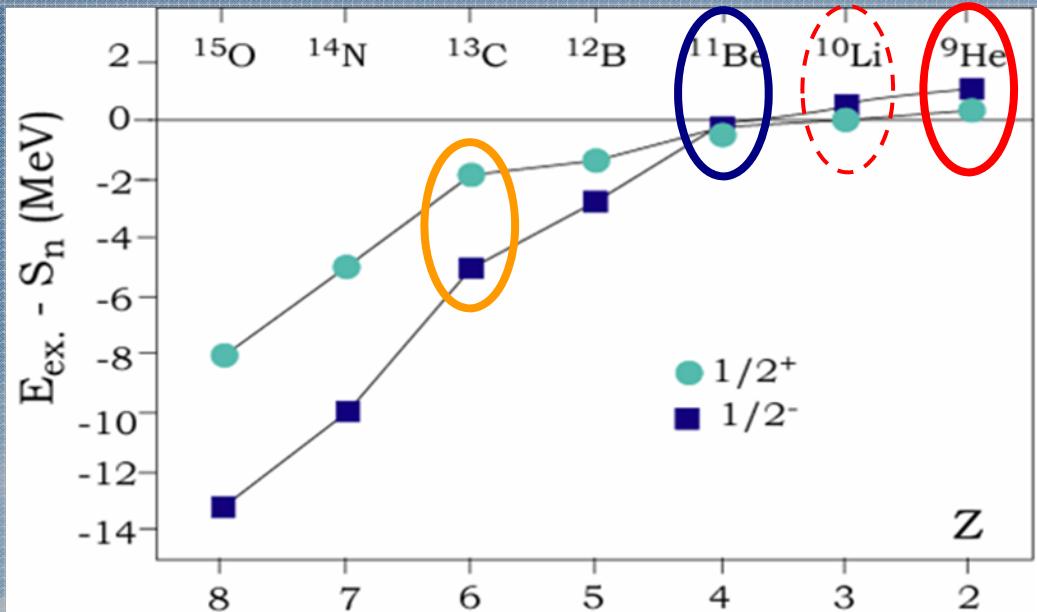


T.Otsuka et al., Phys. Rev. Lett. 87 (2001) 082502

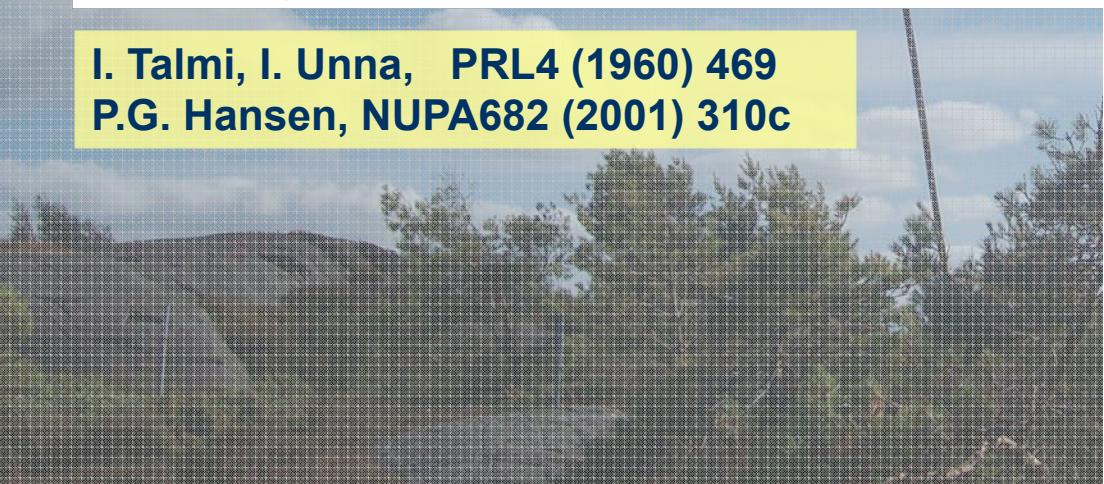
$Z=14 \rightarrow Z=8$: Removing $0d_{5/2}$ protons

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

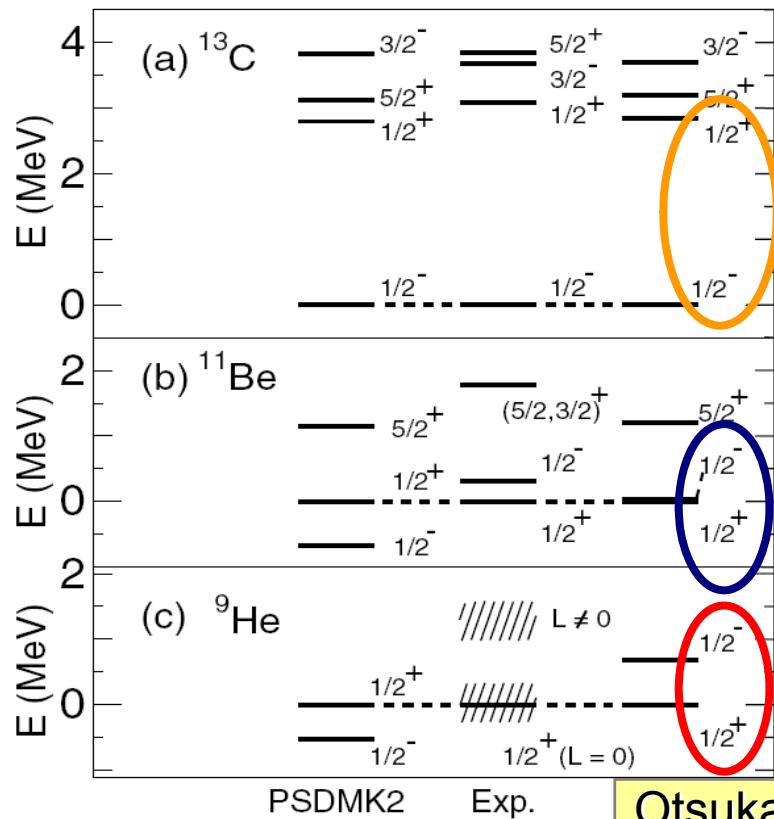
Otsukas prediction: intruder states



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

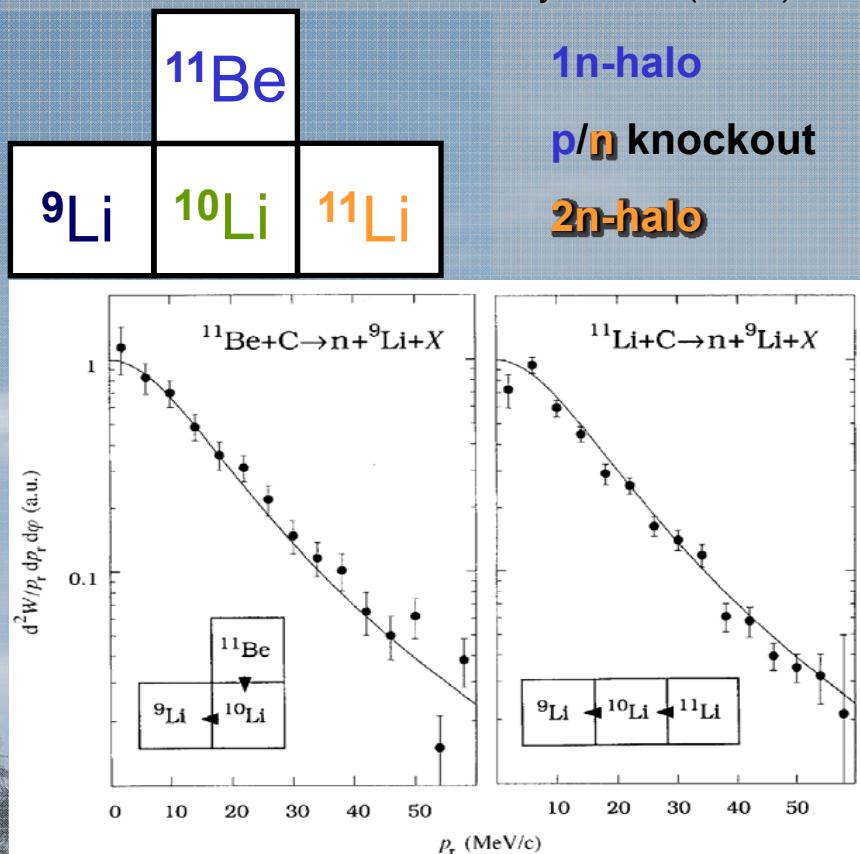
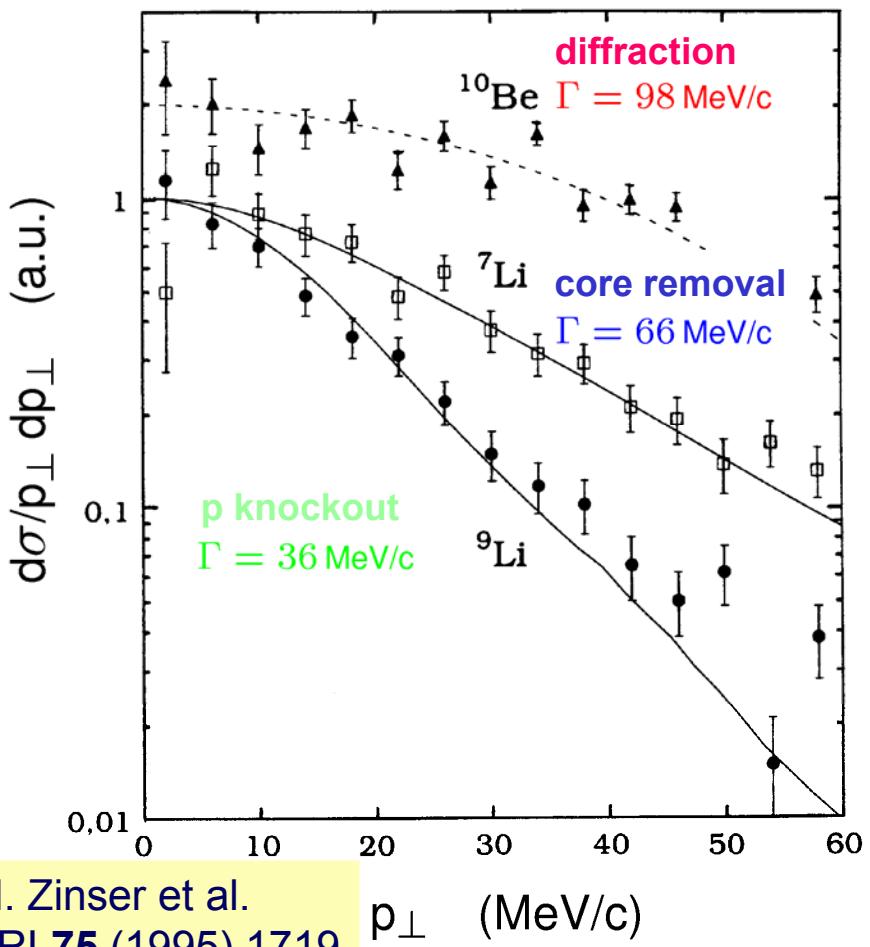


T. Otsuka et al.,
Phys. Rev. Lett. 87 (2001) 082502



Starting Point: Neutron Momentum Distributions

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



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)

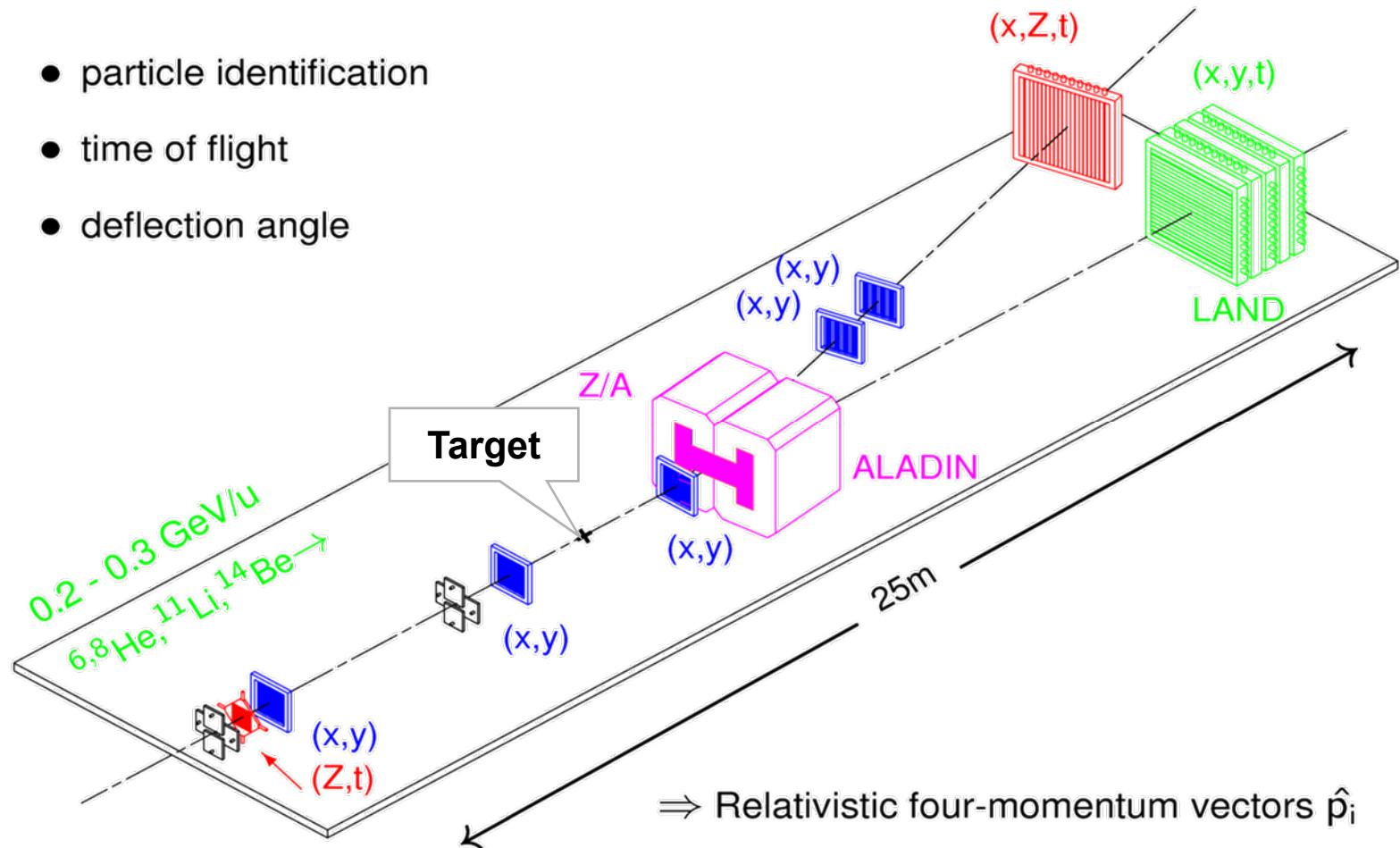
- clean production and detection
- relative energy measurement
- J^π assignment

Challenges

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

Experimental Setup (kinematically complete)

- particle identification
- time of flight
- deflection angle



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

Toolbox:

Momentum of the knocked out neutron ? (groundstate property)

→ missing momentum

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

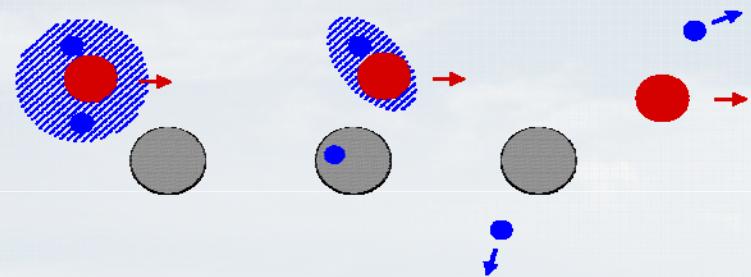
Spectroscopy of intermediate system

→ relative energy from relative momentum

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

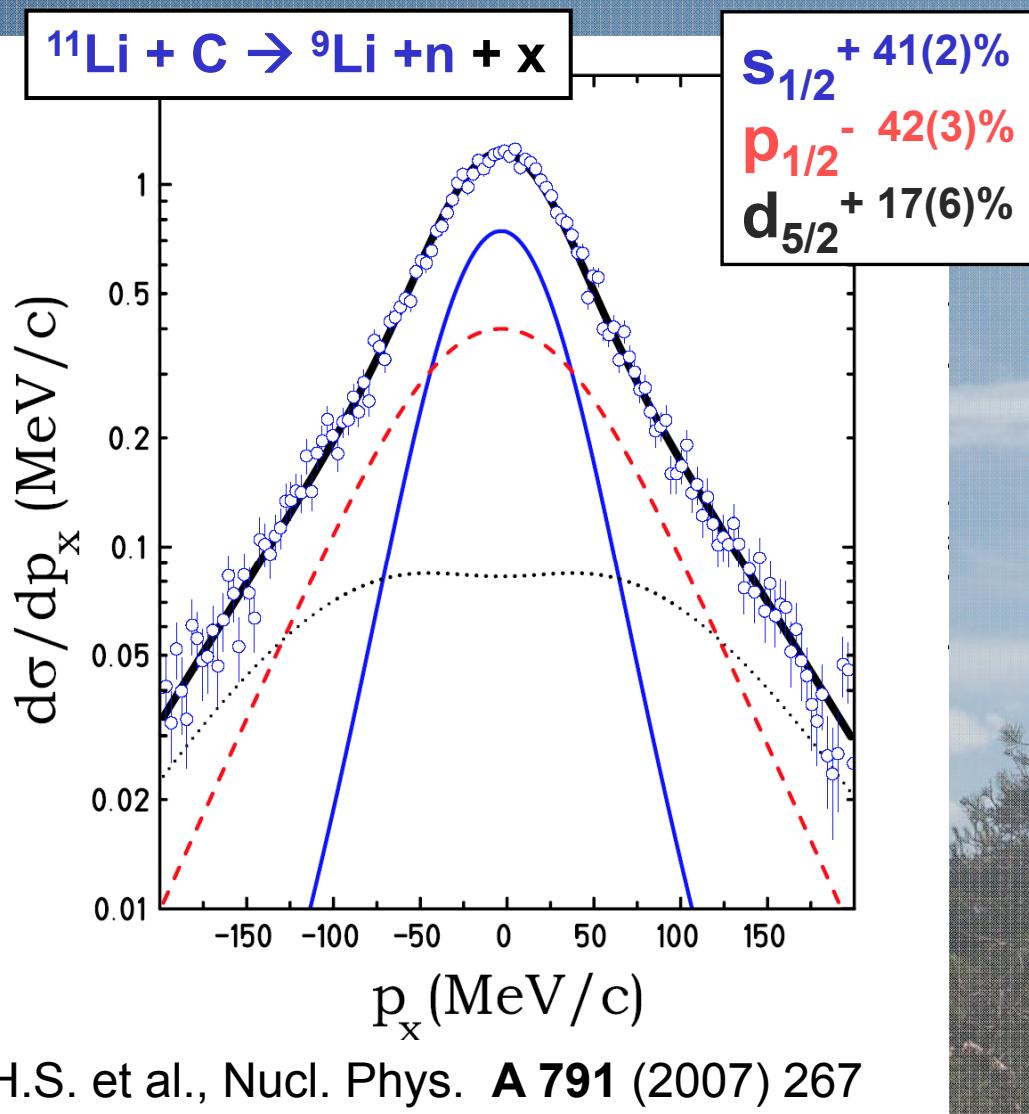
$$E_{fn} = p_{fn}^2 / 2\mu$$

... or invariant mass via Mandelstam s



^{11}Li : Missing momentum distribution

$$p_m = (p_f + p_n)$$



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

- $k = (2 \mu S_n)^{-1/2}$
from ${}^{10}\text{Li}$ relative energy spectrum

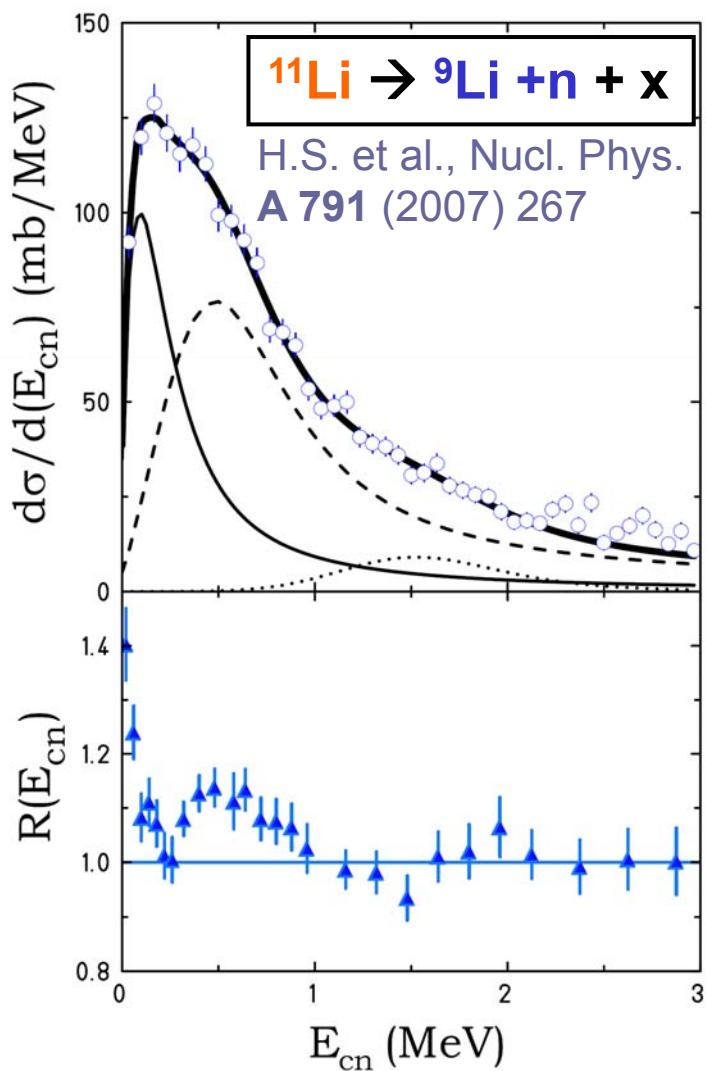
- core survival \leftrightarrow cylindrical cut

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

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

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

$^{11}\text{Li} \rightarrow ^{10}\text{Li}$: Relative energy spectrum



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

- steep rise at threshold $\rightarrow \ell = 0$

-30^{+12}_{-31} fm; virt.
0.51(44); 0.54(16)
1.49(88); < 2.2

$E^*; \Gamma$
in MeV

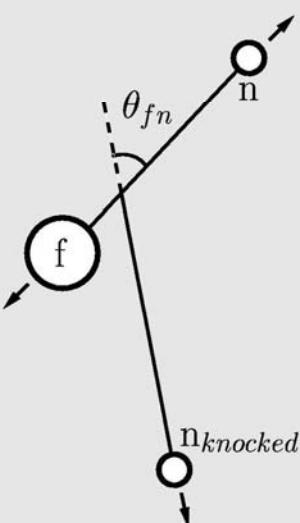
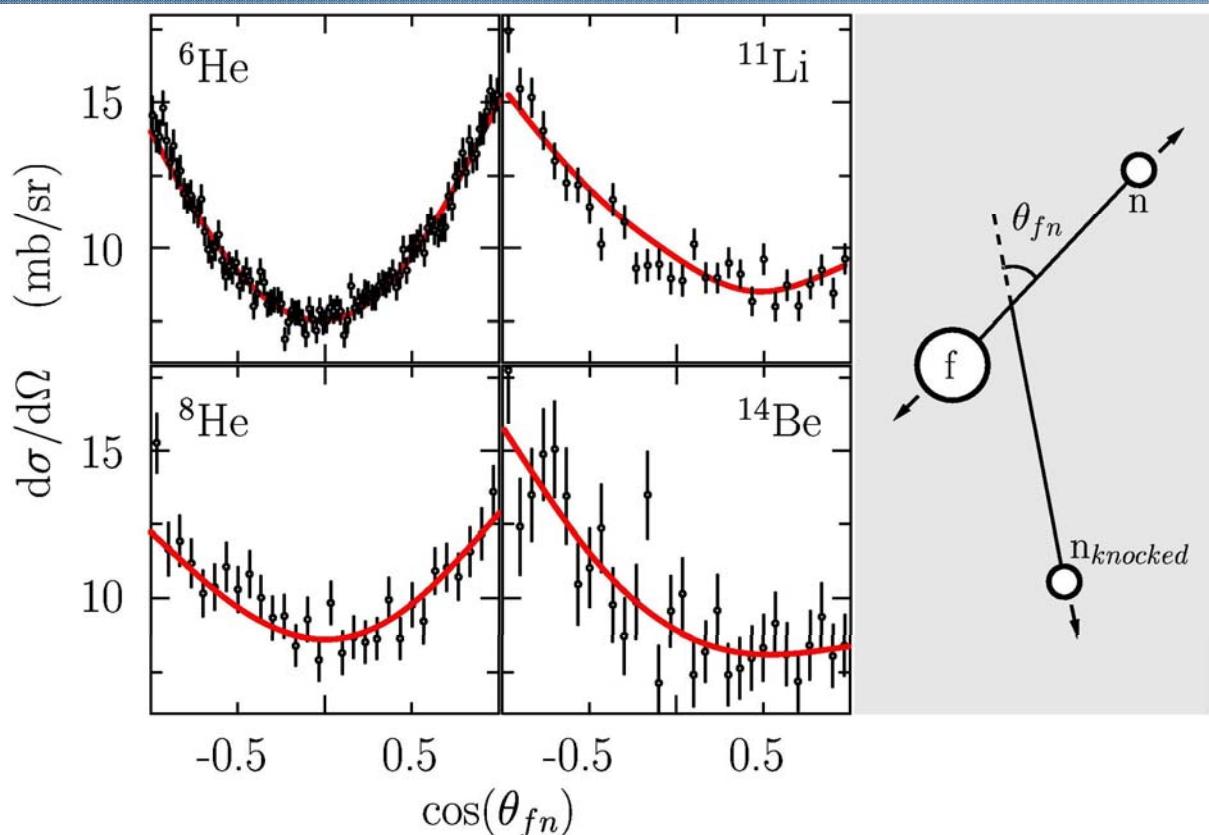
- confirmed by ang. correlations
($-22.4(4.8)$ fm / 0.566(14) MeV IH_2 target)
- correlated events ?

$$R = d\sigma/dE / d\sigma/dE_{\text{mix}}$$

- spin assignment ?

2n-Halo : n-n angular correlations

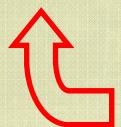
$$\cos(\theta)_{fn} = \frac{p_m p_{fn}}{p_m p_{fn}}$$



Angular correlations:

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

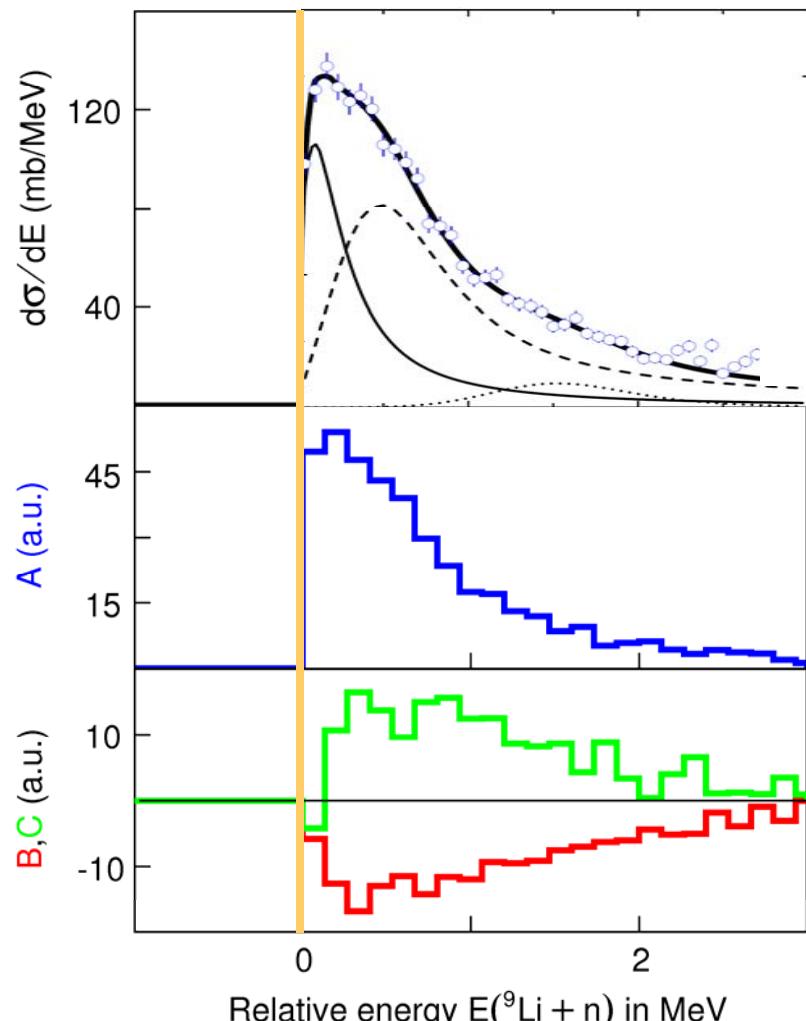
L.V. Chulkov et al.,
Phys Rev. Lett. **79**(1997)201



- momentum transfer small
- **interferring** states of different parity

$^{11}\text{Li} \rightarrow ^{10}\text{Li}$: combining bits and pieces

$$d\sigma/d\Omega \propto A + B \cos \theta_{\text{fn}} + C \cos^2 \theta_{\text{fn}}$$



H.S. et al., NUPA 791 (2007) 267

Conclusion: ^{10}Li

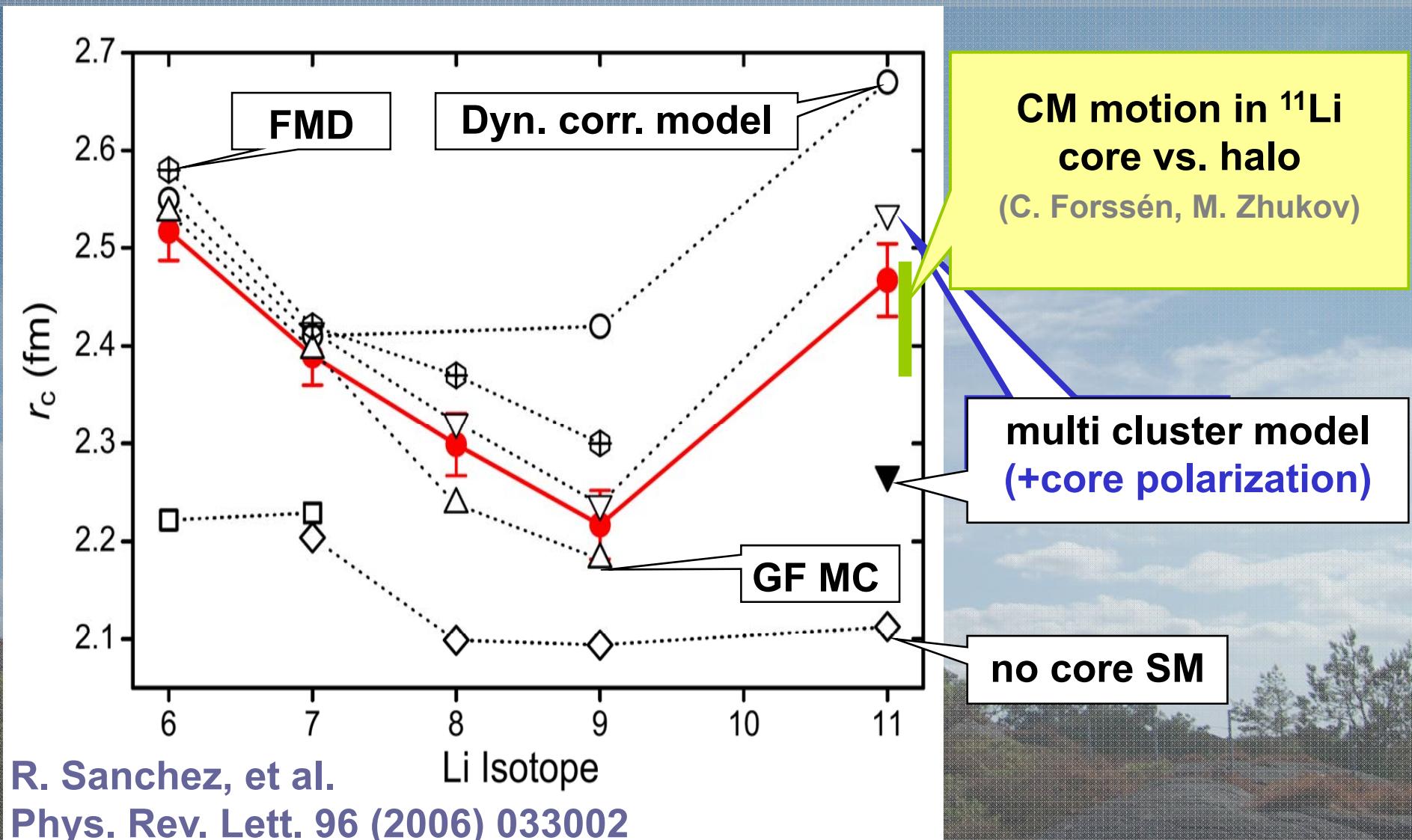
consistent description of observed

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

→ e.g. Garrido/Fedorov/Jensen
NUPA700(2002)117

Application

LASER spectroscopy: charge radii Li isotopes



To calculate the charge radii of ${}^6\text{He}$ or ${}^{11}\text{Li}$ we need to know the charge radius of the cores ${}^4\text{He}$ and ${}^3\text{Li}$ (r_{ch}) and the distances of the cores (ΔR_c) from the center of mass of the corresponding nuclei (${}^6\text{He}$, ${}^{11}\text{Li}$)

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

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

$\Delta R_c({}^4\text{He})$ 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

$$S_{\text{clus.}}^{\text{NEW}} = \frac{3}{4\pi} Z_c^2 e^2 (\Delta R_c({}^4\text{He}))^2 \leftrightarrow \Delta R_c^{\text{exp.}}({}^4\text{He}) = 1.12 \pm 0.13 \text{ or theor. calculations}$$

[B.V. Davilin... NPA 632 (1998) 383] $\leftrightarrow \Delta R_c^{\text{th.}}({}^4\text{He}) = 1.2$

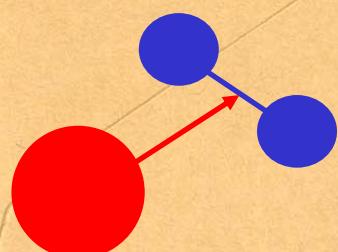
$$r_{ch}^{\text{exp.}}({}^6\text{He}) = 1.944 \div 2.088 \text{ fm}$$

$$r_{ch}^{\text{th.}}({}^6\text{He}) = 2.059 \text{ fm}$$

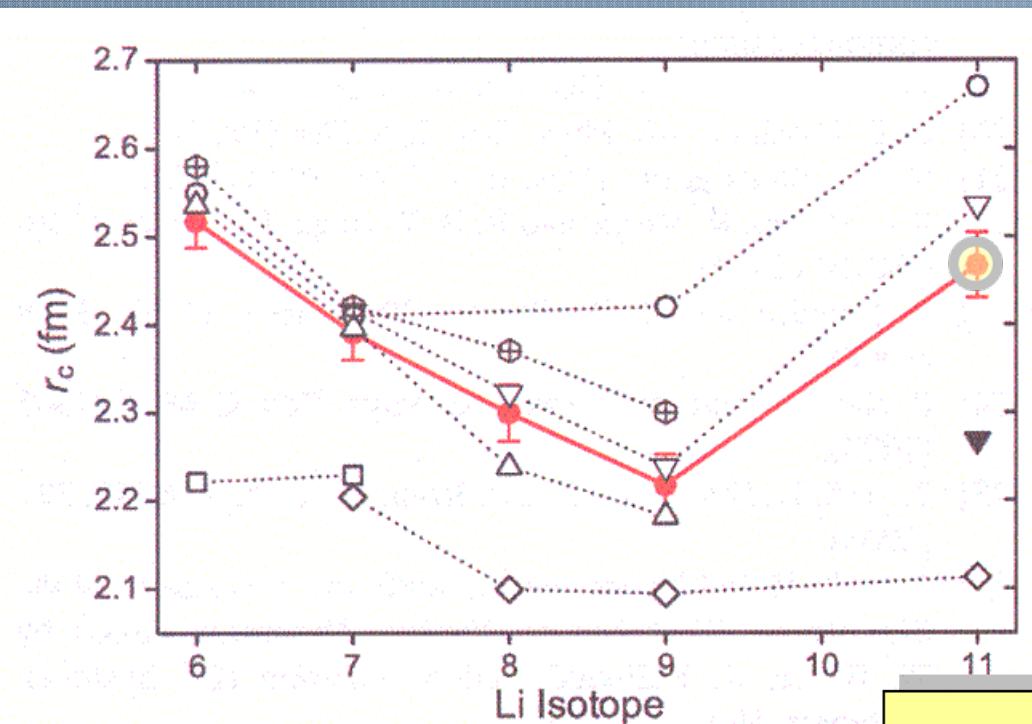
$({}^{11}\text{Li}) r_{ch}({}^3\text{Li}) = 2.24 \pm 0.04$ [G. Eward..., PRL 94 (2005) 032501]

$\Delta R_c({}^3\text{Li})$ is not known experimentally. From theor. paper [Ch. Forssen... NPA (2002) 48] we can get two values: $\Delta R_c^{\text{th.}}({}^3\text{Li}) = 1.08$ or $\Delta R_c^{\text{th.}}({}^3\text{Li}) = 0.8$, depending on correlations in ${}^{11}\text{Li}$ WF (unknown from exp.).

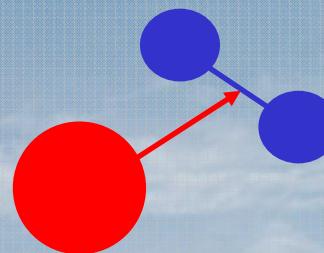
$$r_{ch}^{\text{th.}}({}^{11}\text{Li}) = 2.49 \pm \dots \text{ fm} \quad \text{or} \quad r_{ch}^{\text{th.}}({}^{11}\text{Li}) = 2.38 \pm \dots \text{ fm}$$



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



$\cos(\theta_{fn})$ from exp. !
H.S. et al. PRL 83 (1999) 496



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

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

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

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

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

M.V. Zhukov
N. Shulgina
C. Forssén

^{11}Li : Mass, magnetic moment !

N. Shulgina et al. to be published

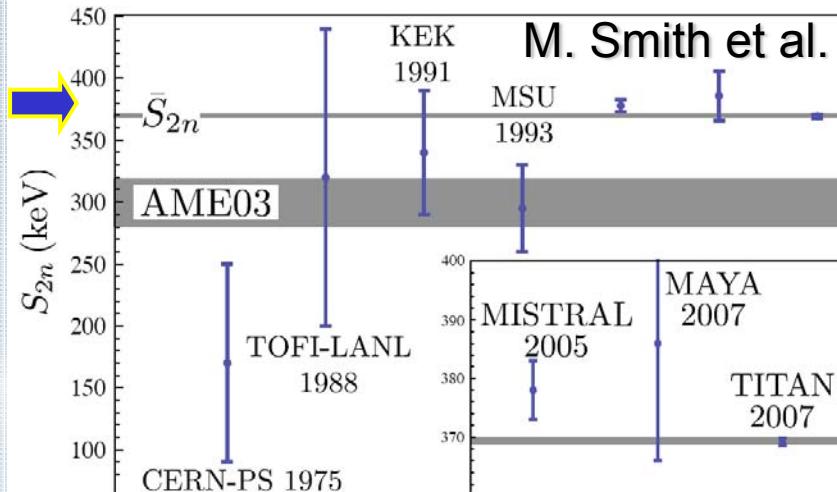
- halo neutrons coupled to $J=0$ (94%), $J=1,2$ (6%)
just 3 harmonics $K=0,2$

$$\begin{array}{lll} \mathbf{T}: & K=2 & l_x, l_y=1,1 \quad S=1 \\ & 0,0 & 0 \\ \mathbf{T}: & K=0 & 0,0 \quad 0 \end{array}$$

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

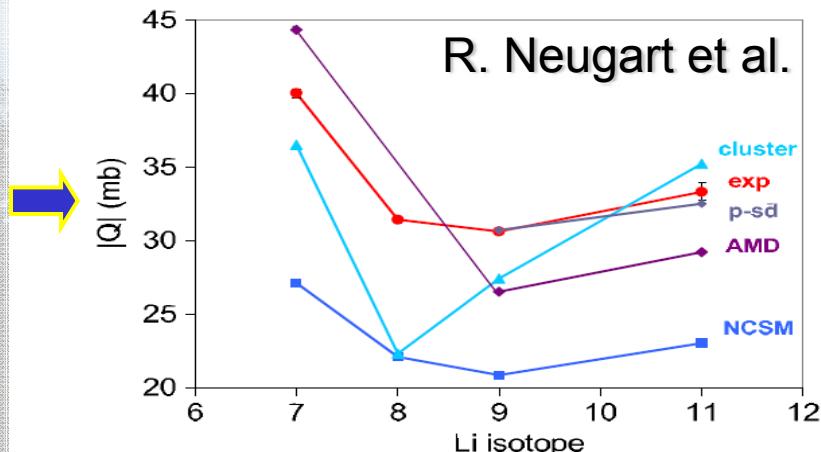
Result (consistent description):

- 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)

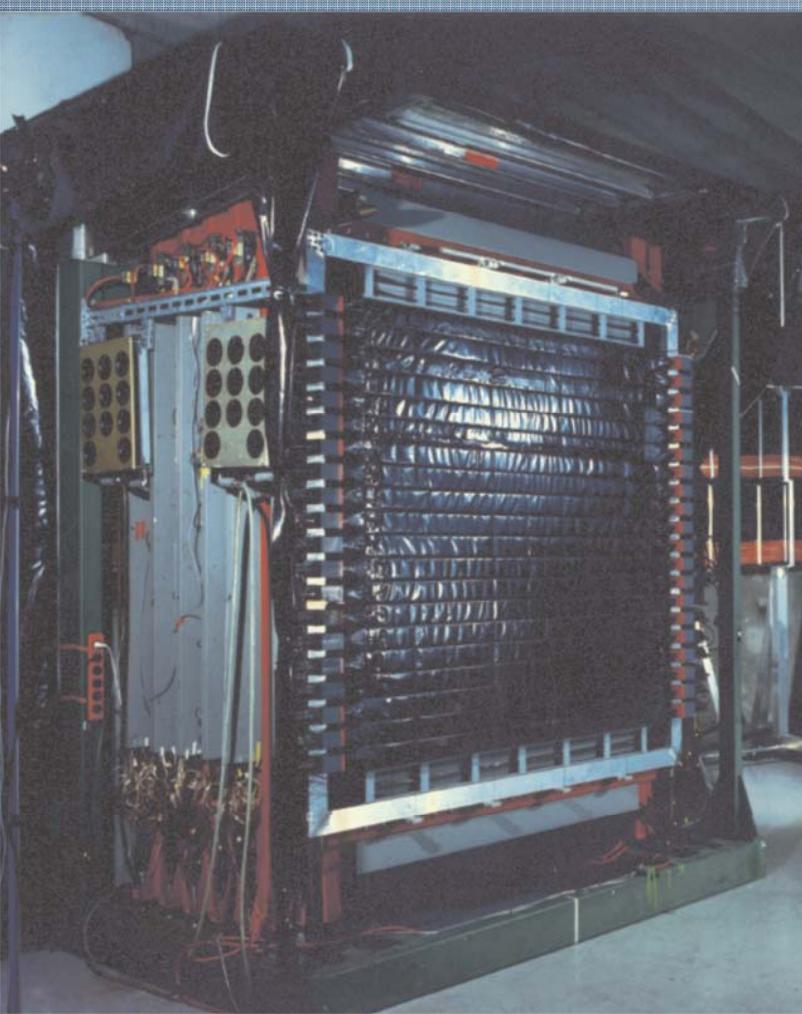


PRL 101, 132502 (2008)

PHYSICAL

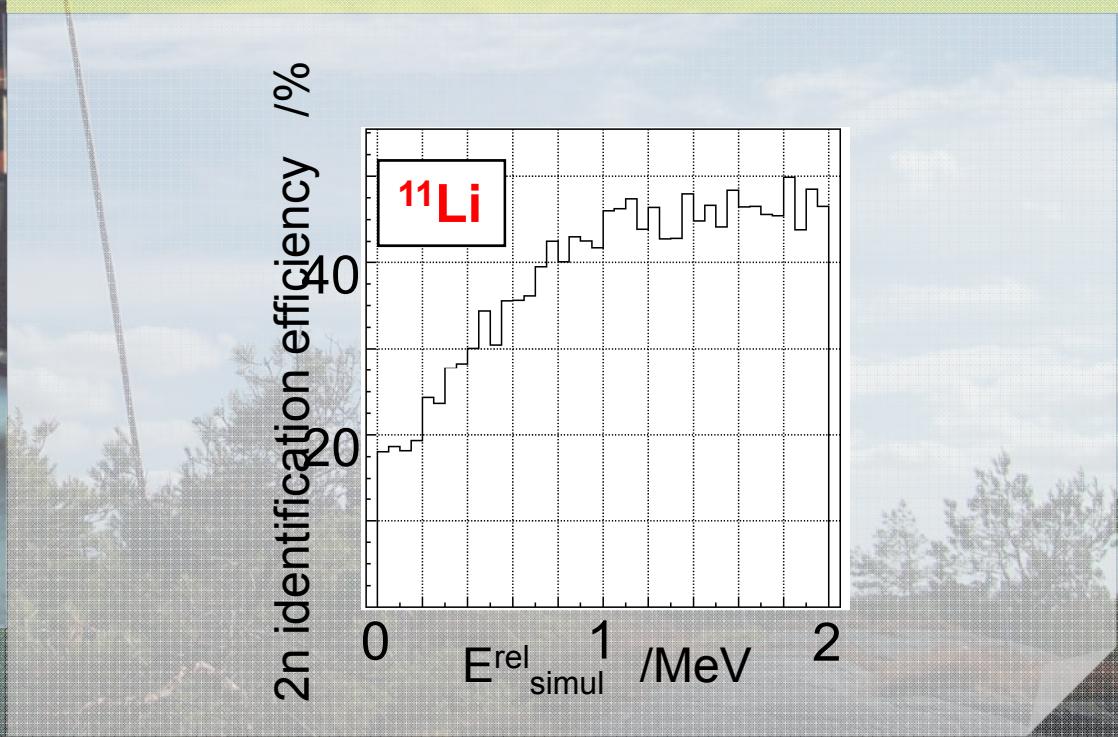


Three-body Continuum Spectroscopy: prerequisites



→ compute relative energy of all particles emerging from target

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

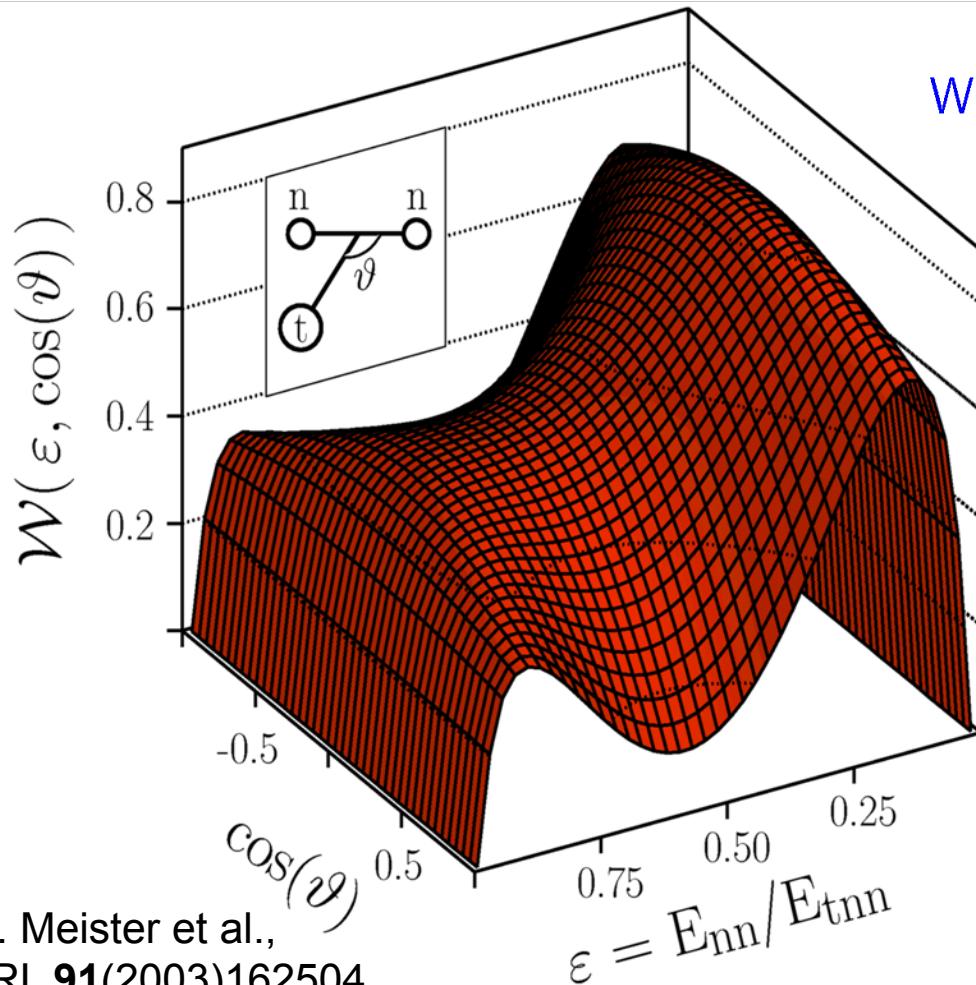


Nucl. Instr. Meth. A314 (1992) 136

Beyond the dripline: ${}^5\text{H}$

N.B. Shulgina et al., Phys.Rev. **C62** (2000) 014312

${}^6\text{He} + \text{C} \rightarrow \text{t} + \text{n} + \text{n}$: proton knockout from the ${}^6\text{He}$ core !



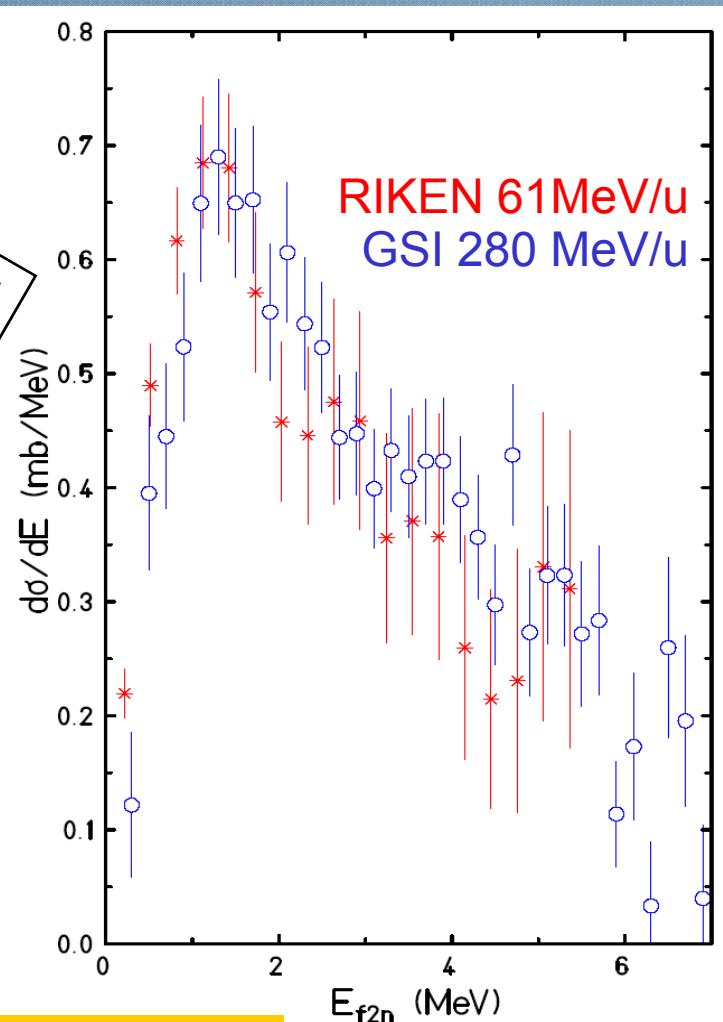
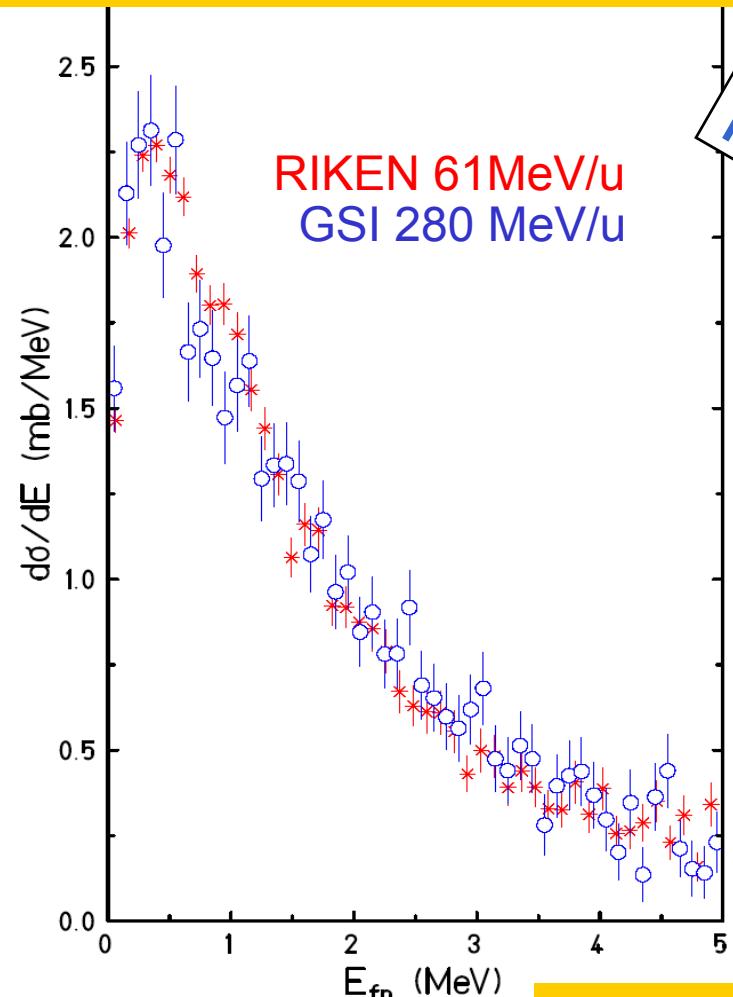
M. Meister et al.,
PRL **91**(2003)162504

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

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

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

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



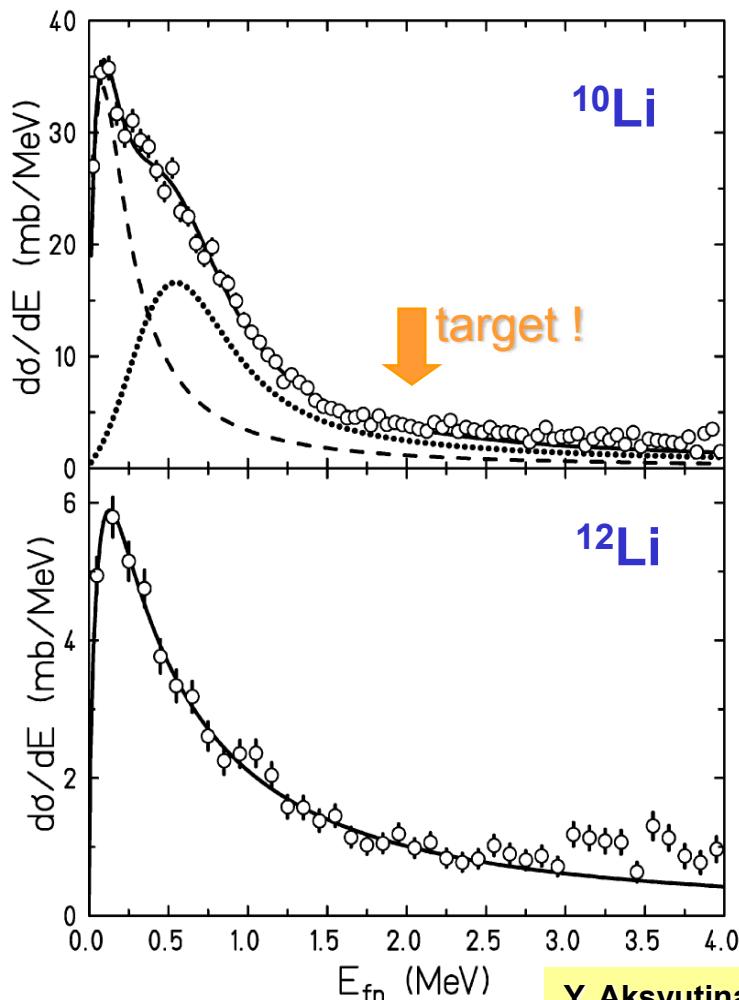
- Consistent with old data set
- Weak ${}^{11}\text{Li}$ beam (background !)

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

Unbound Lithium isotopes



Bertsch, Hencken, Esbensen
PRC57(1998)1366



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

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

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

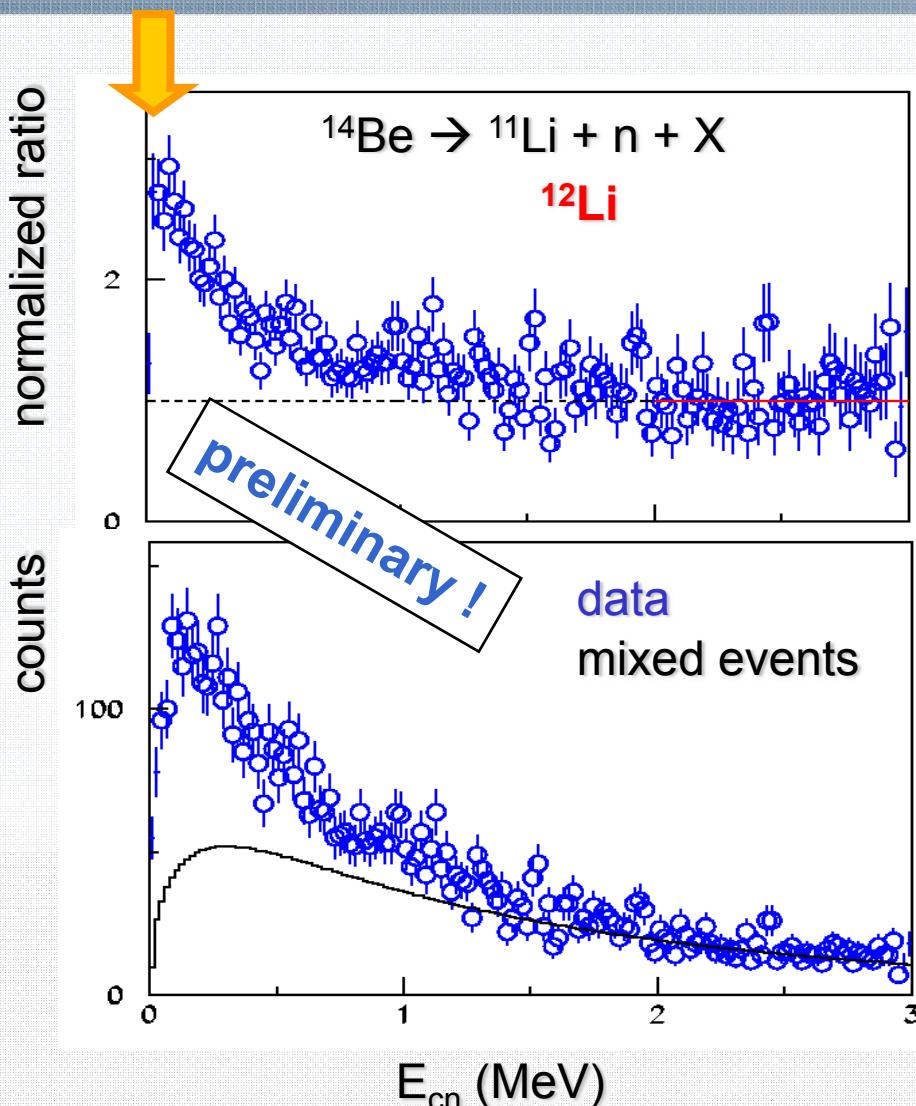
S_n 0.35(22)
 $\approx S_{2n}$ ^{11}Li

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

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

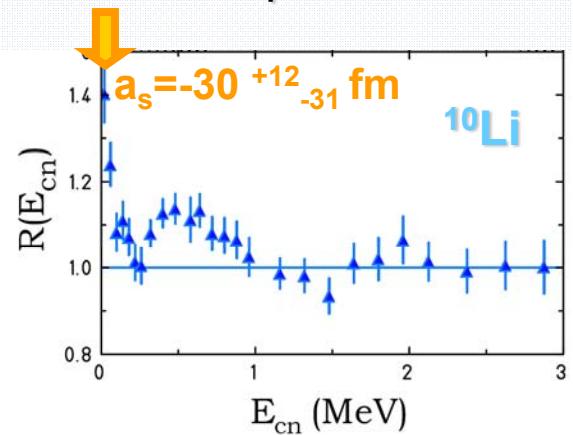
Y. Aksyutina, H. Johansson et al.,
Phys. Lett. B666 (2008) 430

Unbound Lithium isotopes: ^{12}Li



→ strongly correlated events !

→ no two components as in ^{10}Li



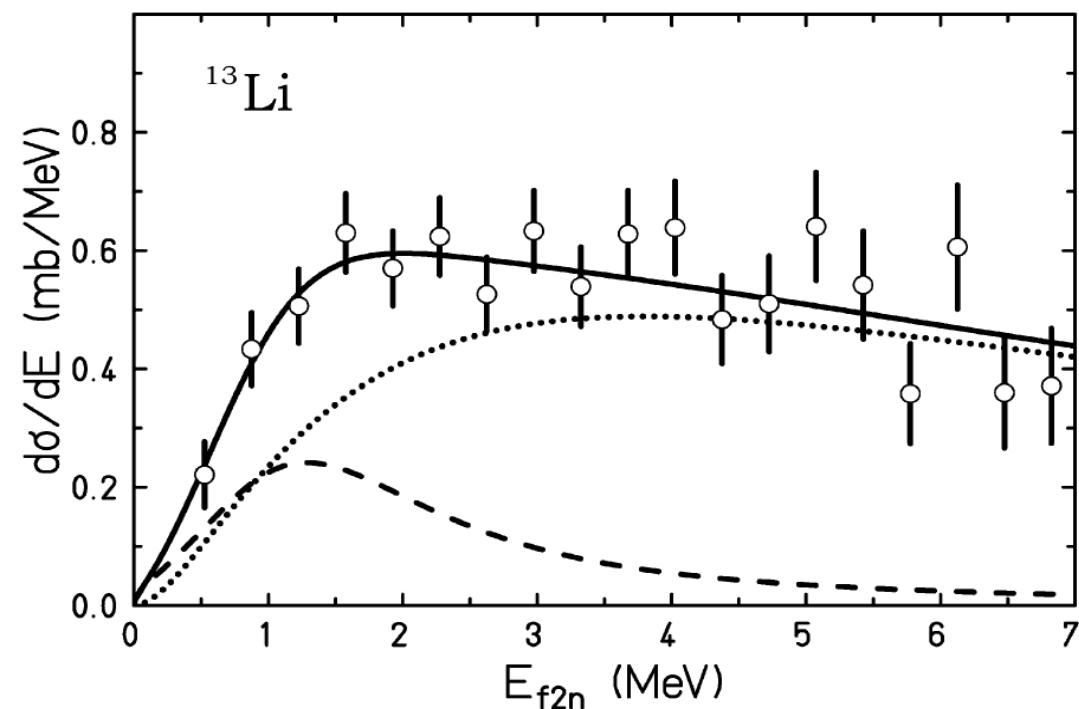
→ steep rise at threshold

→ virtual scattering state

Unbound Lithium isotopes



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



C. Forssén, B. Jonson, M.V. Zhukov
NPA673 (2008) 143

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

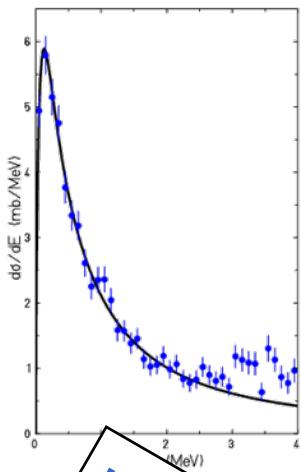
→ $^{11}\text{Li} + 2n$ resonance picture

Evidence for existence
at 1.47(31) MeV

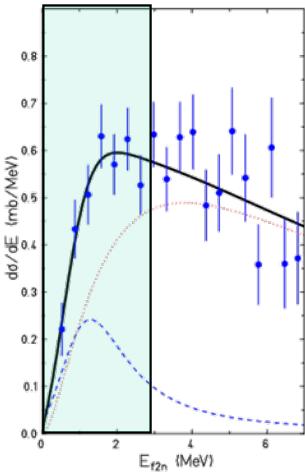
Y. Aksyutina, H. Johansson et al., Phys. Lett. B666 (2008) 430

Comparison ^{10}He and ^{13}Li

^{12}Li



^{13}Li



Yu.Aksyutina, H.Johansson *et al.* **PLB 666** (2008) 434,
and in preparation

^{13}Li

$E_0=1.5(3)$ MeV, $\Gamma_0=2(1)$ MeV

^{10}He

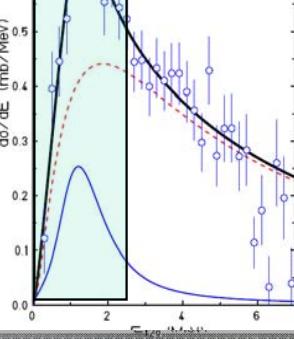
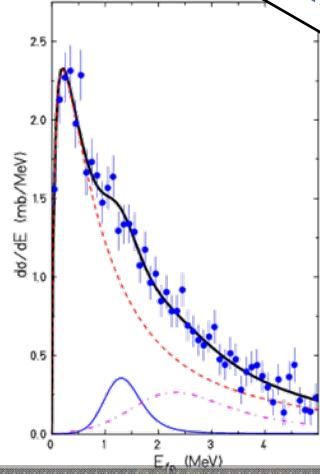
[RIKEN(1994/7),HMI(1994)]

$E_0=1.3(1)$ MeV $\Gamma_0=1.1(5)$ MeV

^9He

preliminary!

^{10}He



^{12}Li

$a=-13.7(1.6)$ fm

^9He

[<-10fm MSU (2001) , >-20fm JINR (2007)]

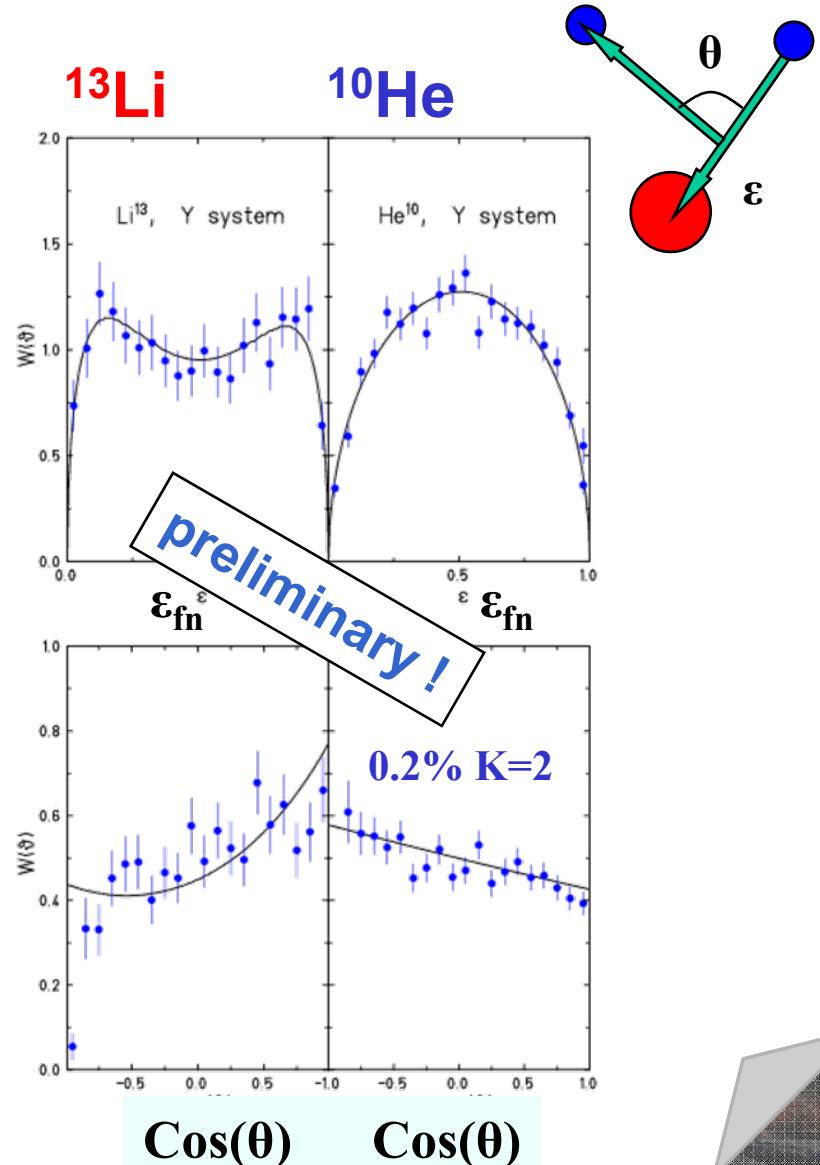
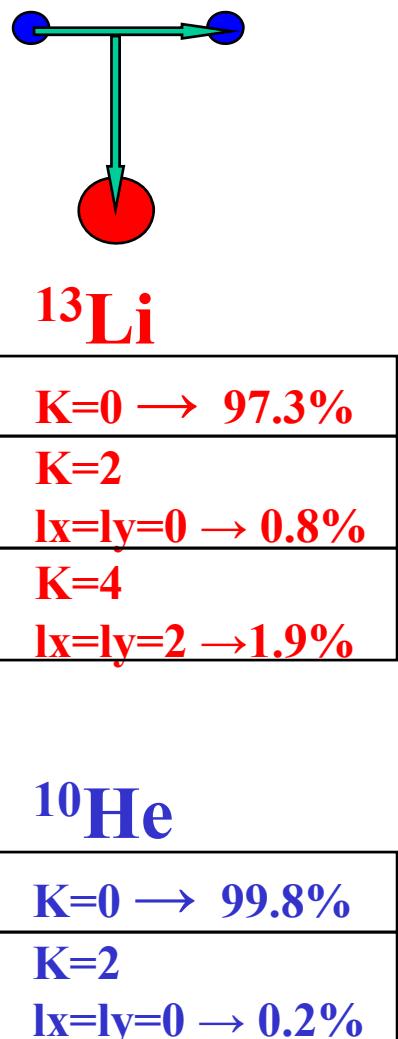
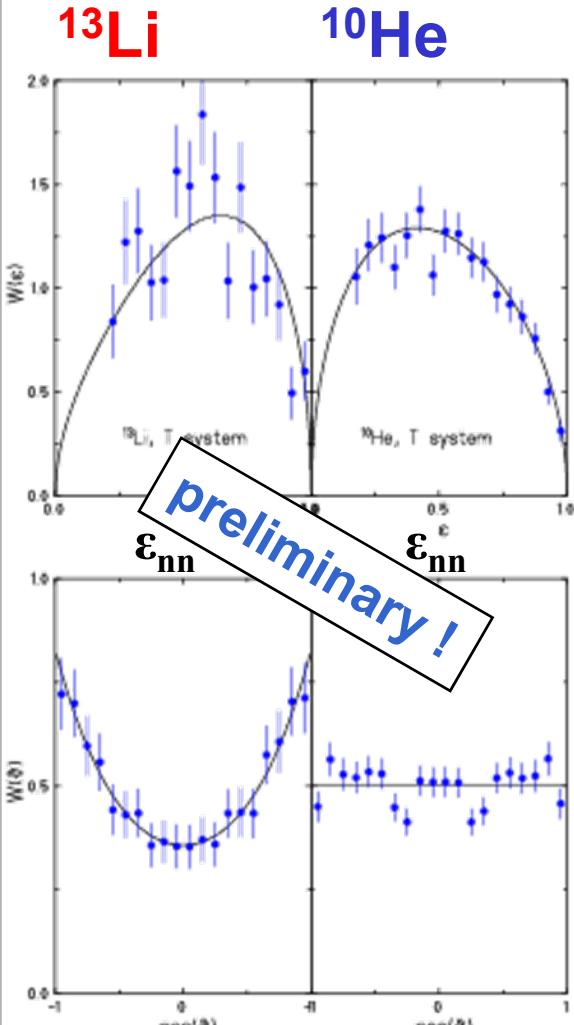
$a=-3.3(5)$ fm, $S_n = 0.71(7)$ MeV

$E_1=1.28(10)$ MeV $\phi=0.15$ MeV
[HMI(1999),JINR(2007)]

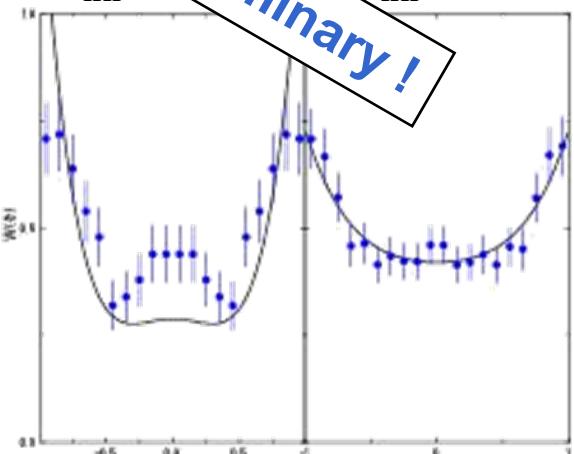
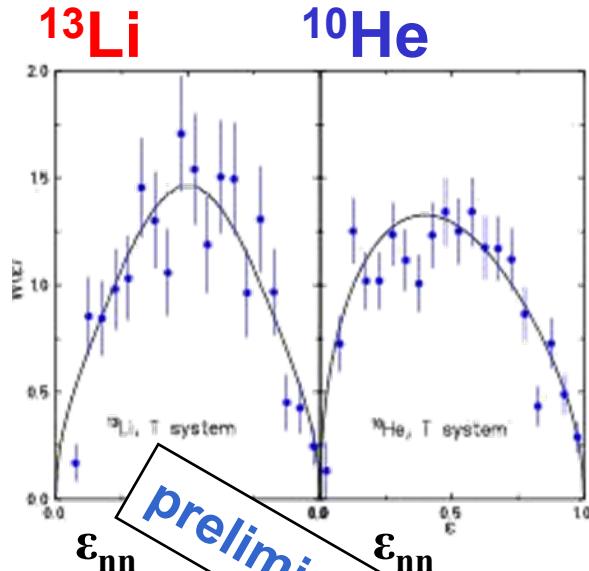
$E_2=2.4$ MeV

$\Gamma=2$ MeV

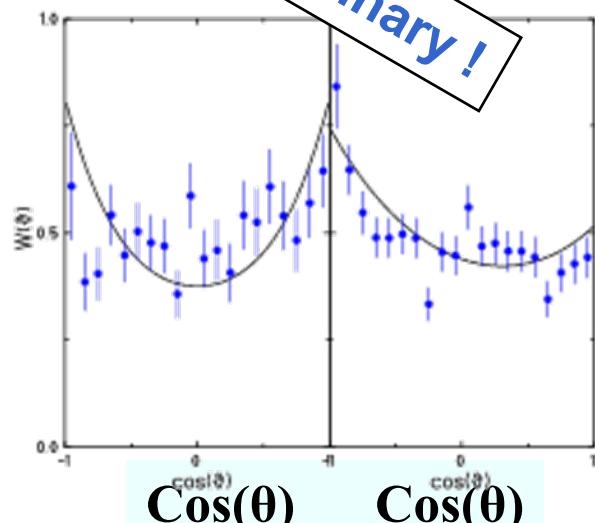
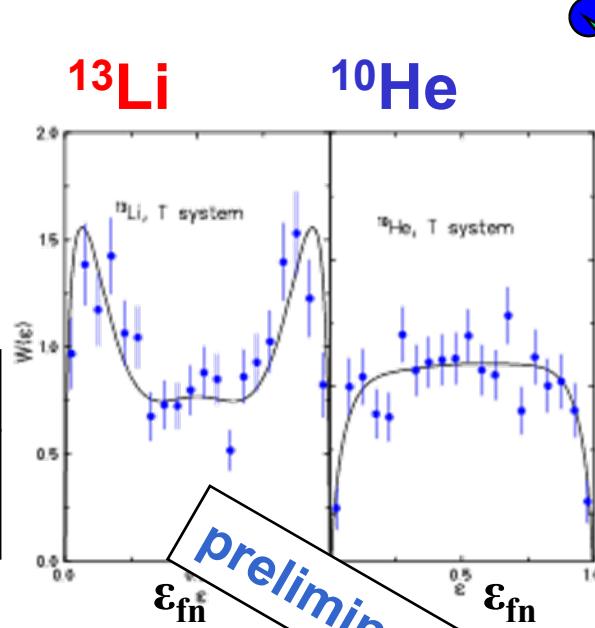
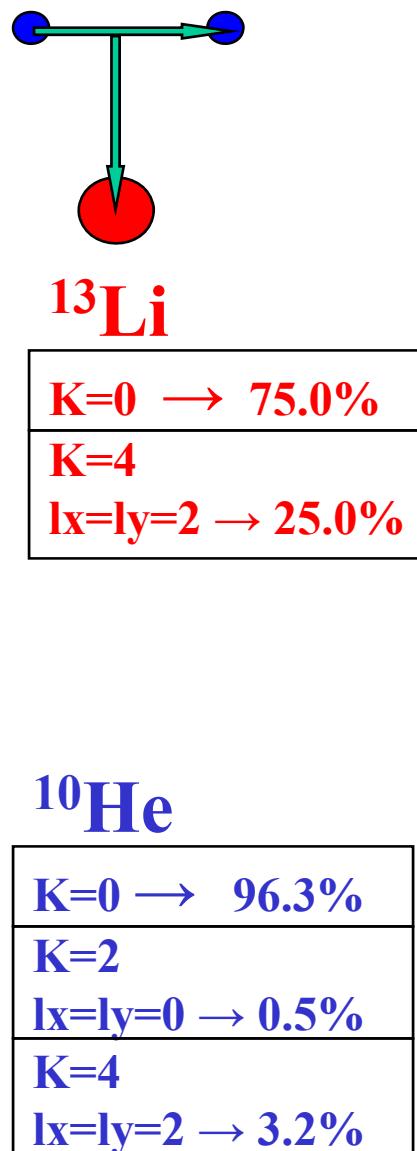
Ground state region 0-3 MeV.



High energy region 3-7 MeV



Cos(θ) **Cos(θ)**



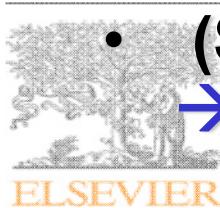
Summary

- 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 !

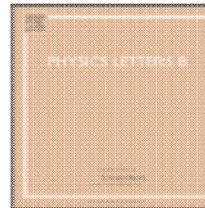
- Heavy H, He isotopes studied
→ spectroscopic data confirmed and continuum structure determined via HH

Physics Letters B 666 (2008) 430–434



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

www.elsevier.com/locate/physletb

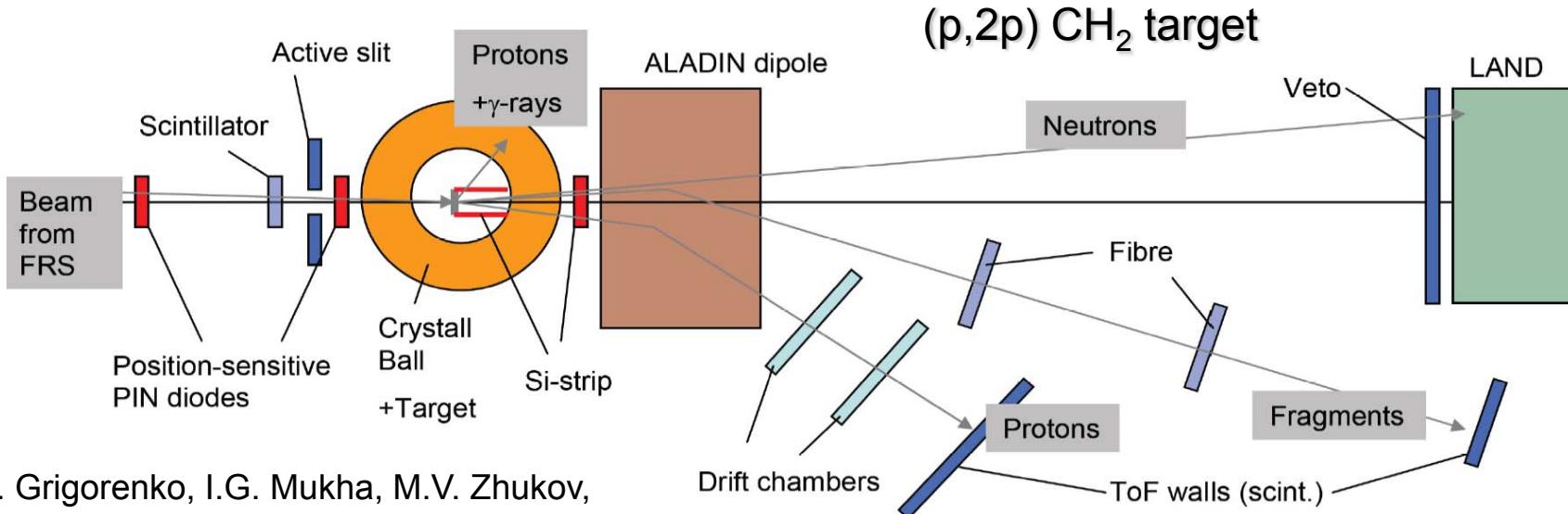


At the horizon: R³B, EXL, ELISe /NUSTAR /FAIR

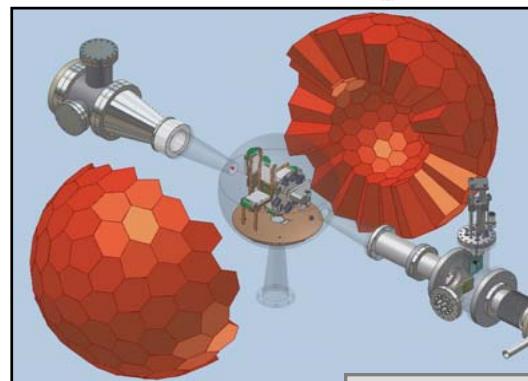
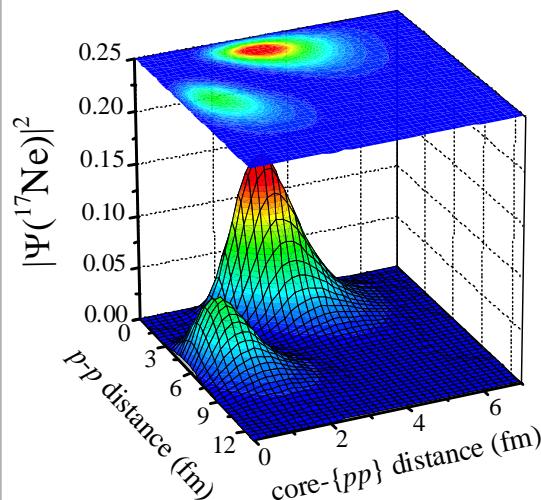


New Experiments (Aug2007 ^{17}Ne , Sep/Oct 2007 ^{12}C QFS, ...)

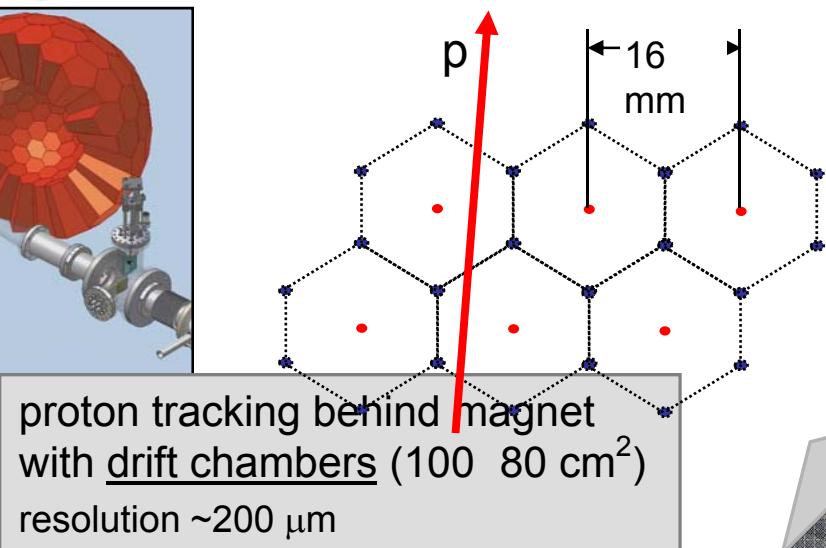
R³B precursor: Setup at Cave C



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



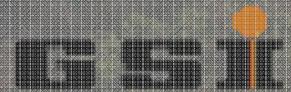
proton and gamma detection



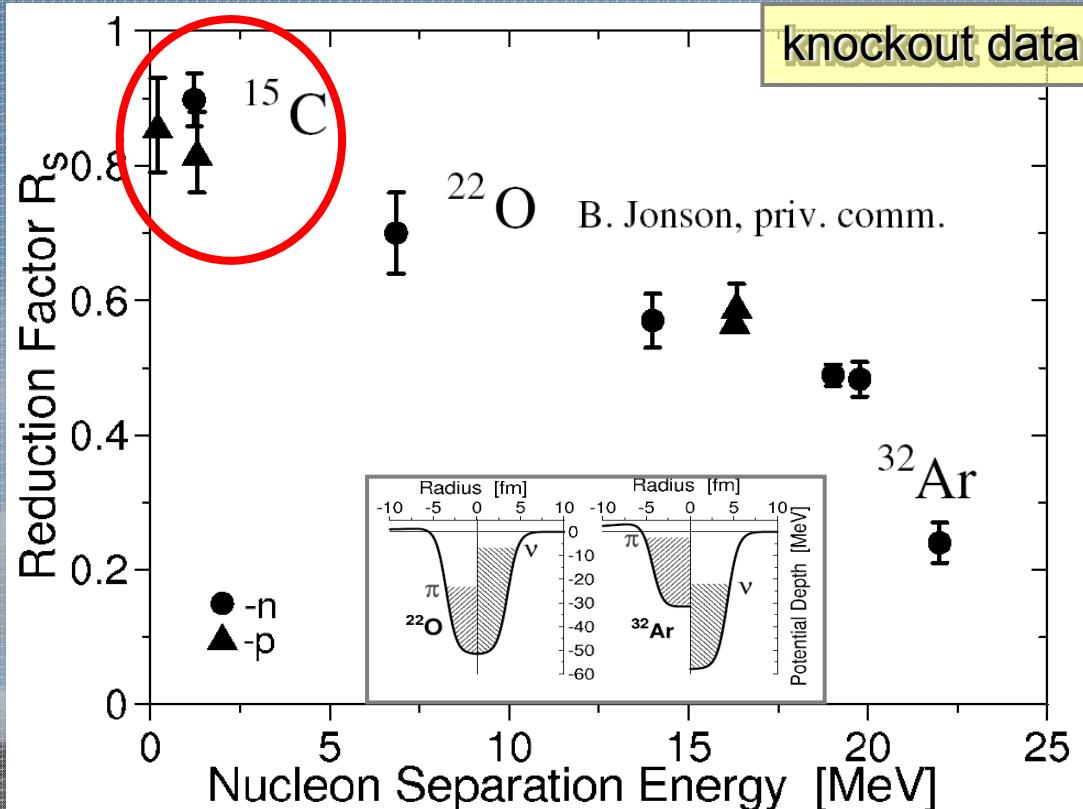
The S135/S245 collaboration

Y. Aksyutina, T. Aumann, H. Álvarez-Pol, T. LeBleis, E. Benjamim, J. Benlliure, M.J.G. Borge, M.Caamaño, E. Casarejos, L.V. Chulkov, D. Cortina-Gil, K. Epinger, Th. W. Elze, H. Emling, C. Forssén, H. Geissel, R. Gernhäuser, A. Grünschloß, M. Hellström, J. Holeczek, K.L. Jones, H. Johansson, B. Jonson, J.V. Kratz, R. Krücken, R. Kulessa, 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. Paschalidis, 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. Sümerer, O. Tengblad, H. Weick, and M.V. Zhukov.

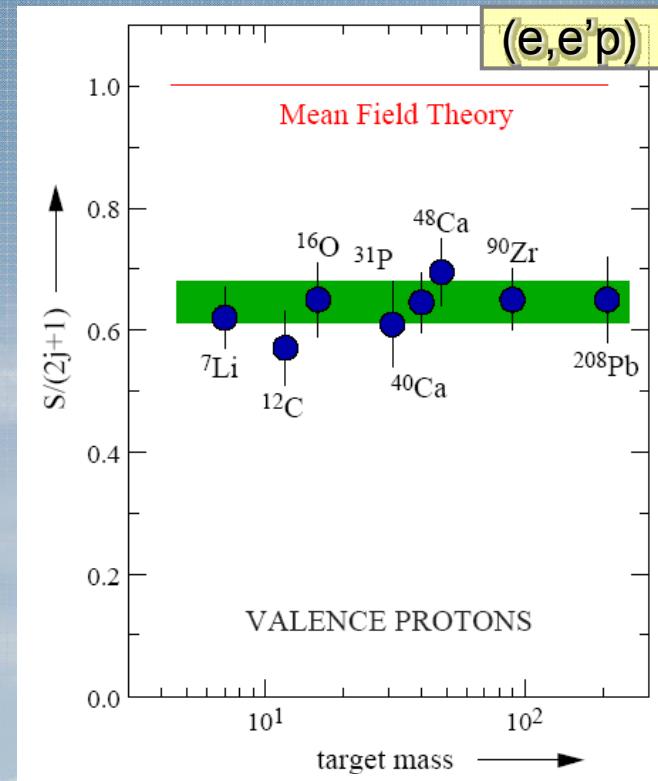
GSI, Darmstadt, Germany; Instituto Estructura de la Materia, Madrid, Spain
Kurchatov Institute, Moscow, Russia; Johann-Wolfgang-Goethe-Universität, Frankfurt, Germany; Chalmers Tekniska Högskola / Göteborgs Universitet, Göteborg, Sweden; Johannes-Gutenberg-Universität, Mainz, Germany; Uniwersytet Jagiellonski,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



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



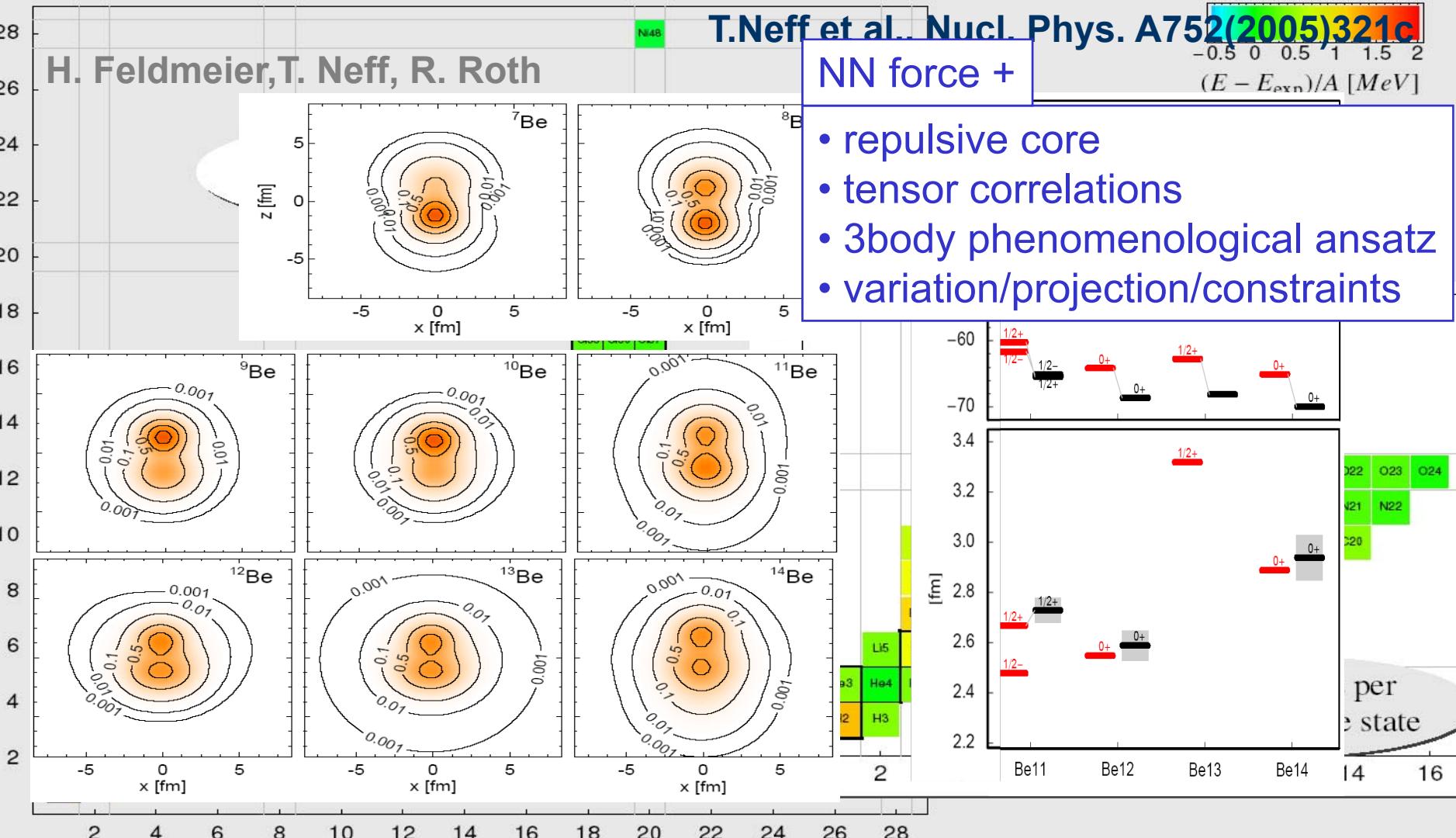
A. Gade et al., Journ. Phys. Conf. **20** (2005) 95



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

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

Clustering: FMD and AV18/UCOM

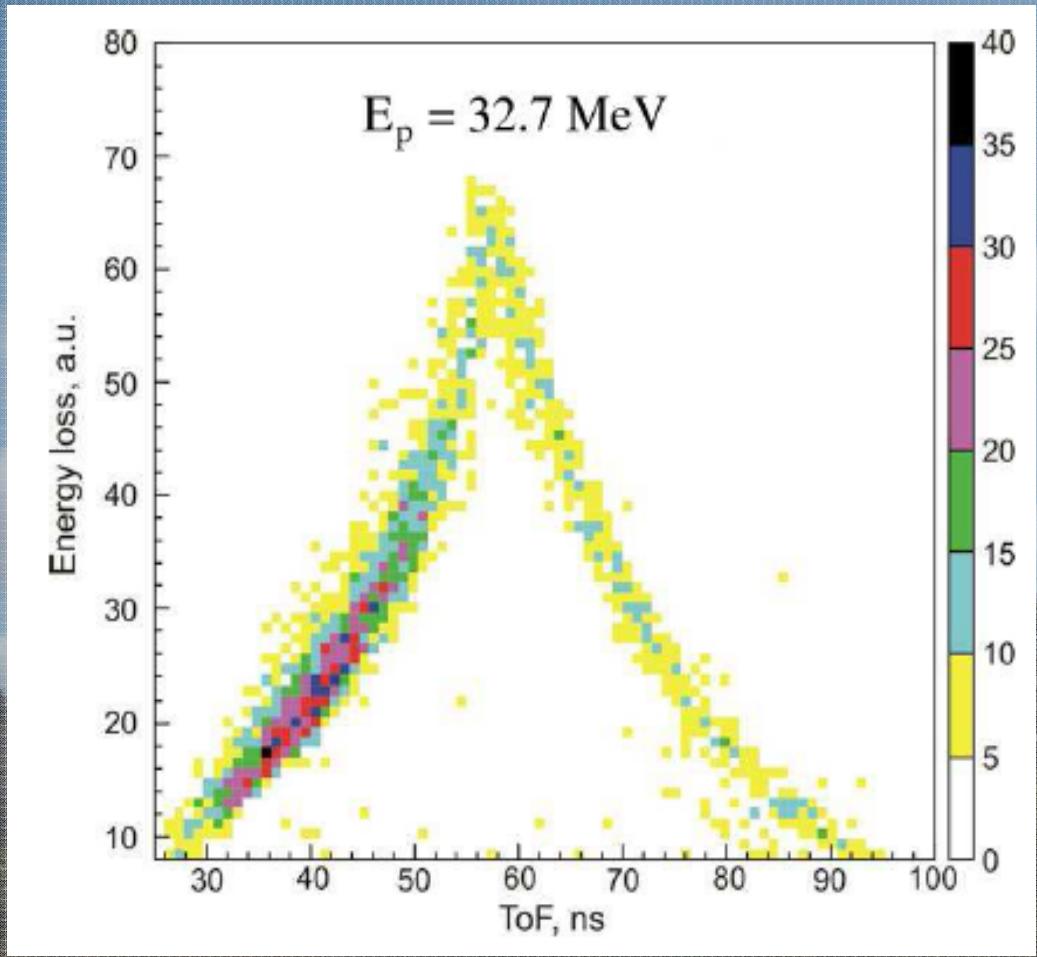


Experimental Setup (less schematic, today)



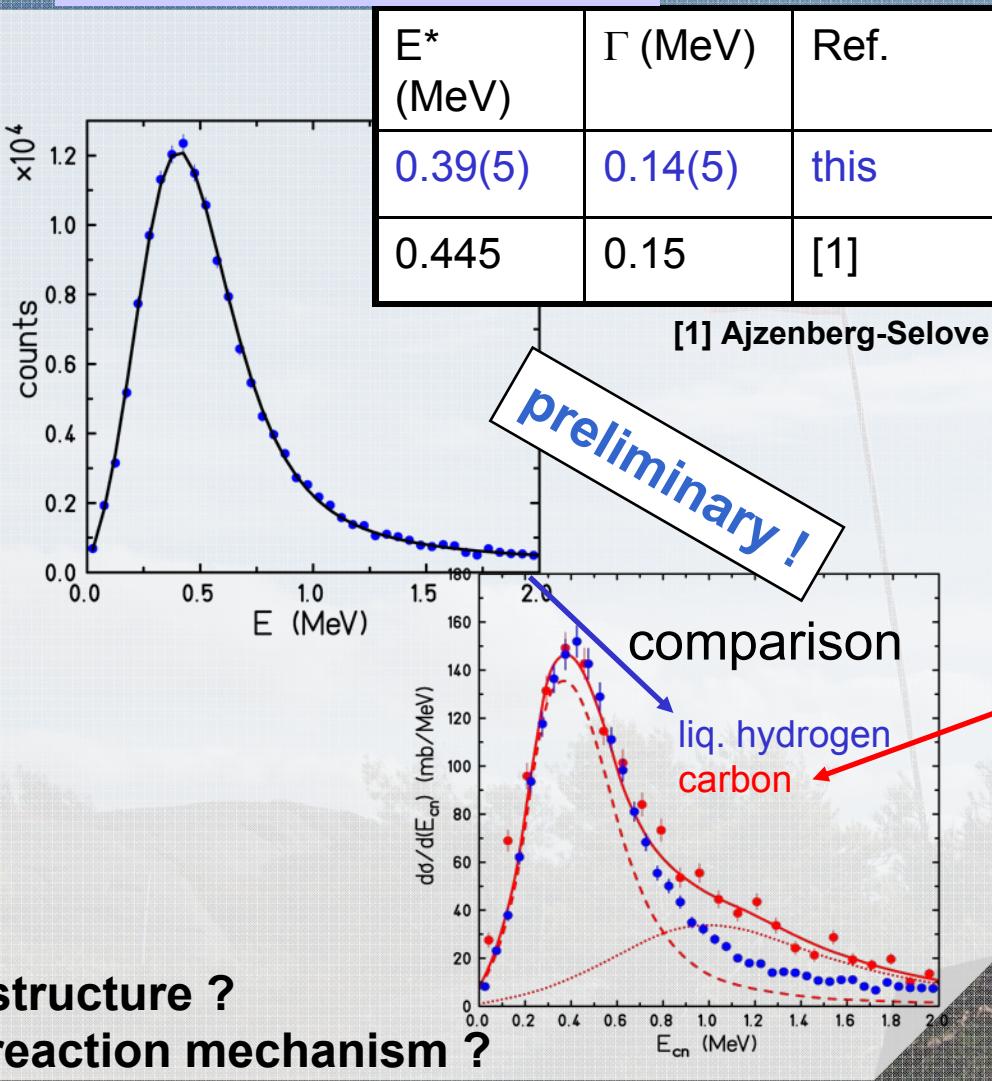
Experimental Setup (less schematic)

Recoil proton detection !



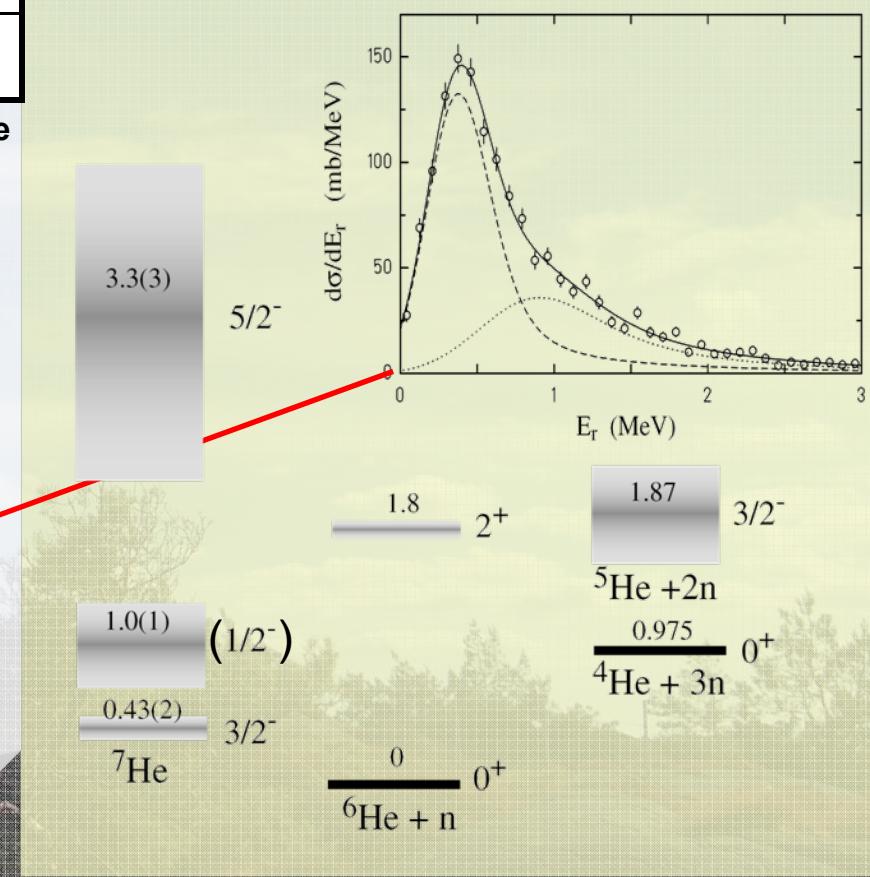
First attempt for an
ALADiN/LAND
experiment 2001...

Unbound Helium isotopes: ^7He target dependence



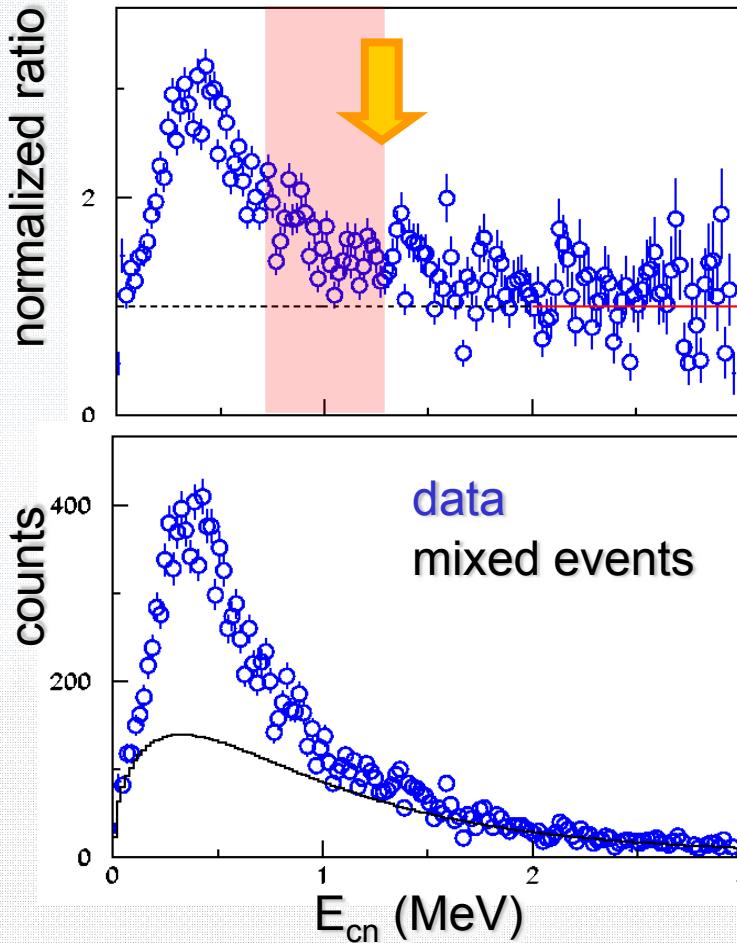
structure ?
reaction mechanism ?

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

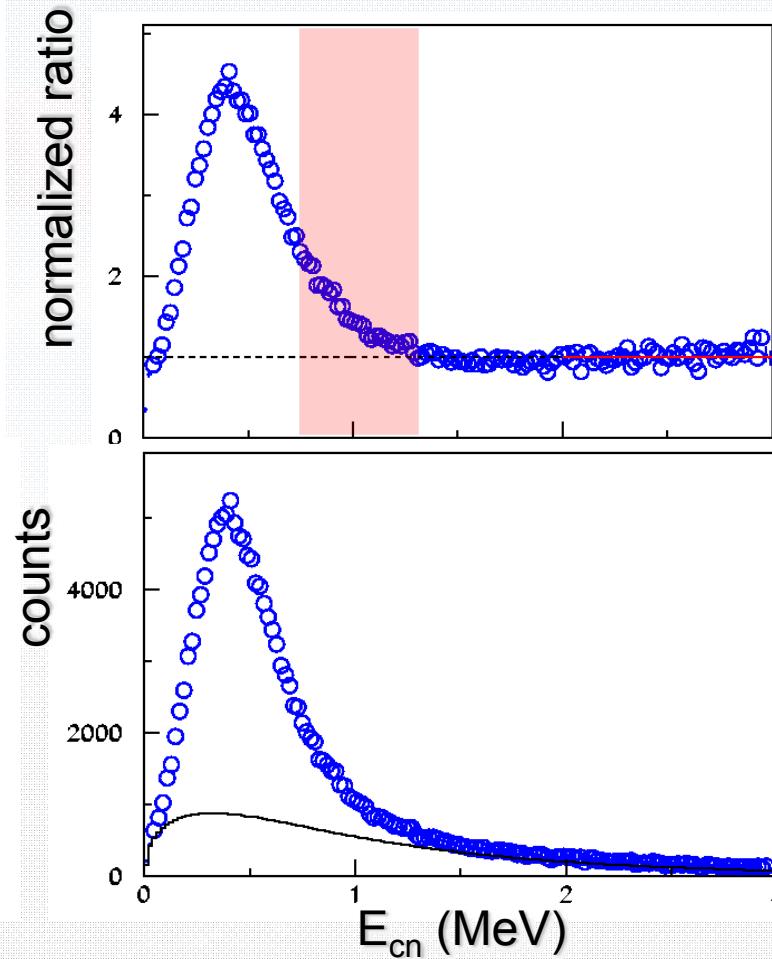


Unbound Helium isotopes: ^7He target dependence

Carbon Data



Proton Data (IH_2)



→ correlated events around $E_{\text{cn}} = 1 \text{ MeV}$ for both targets

→ shapes differ !

→ interpretation ?