1-neutron and 2-protons pick-up reactions to study the unbound nucleus ^{7}He

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DREB2016

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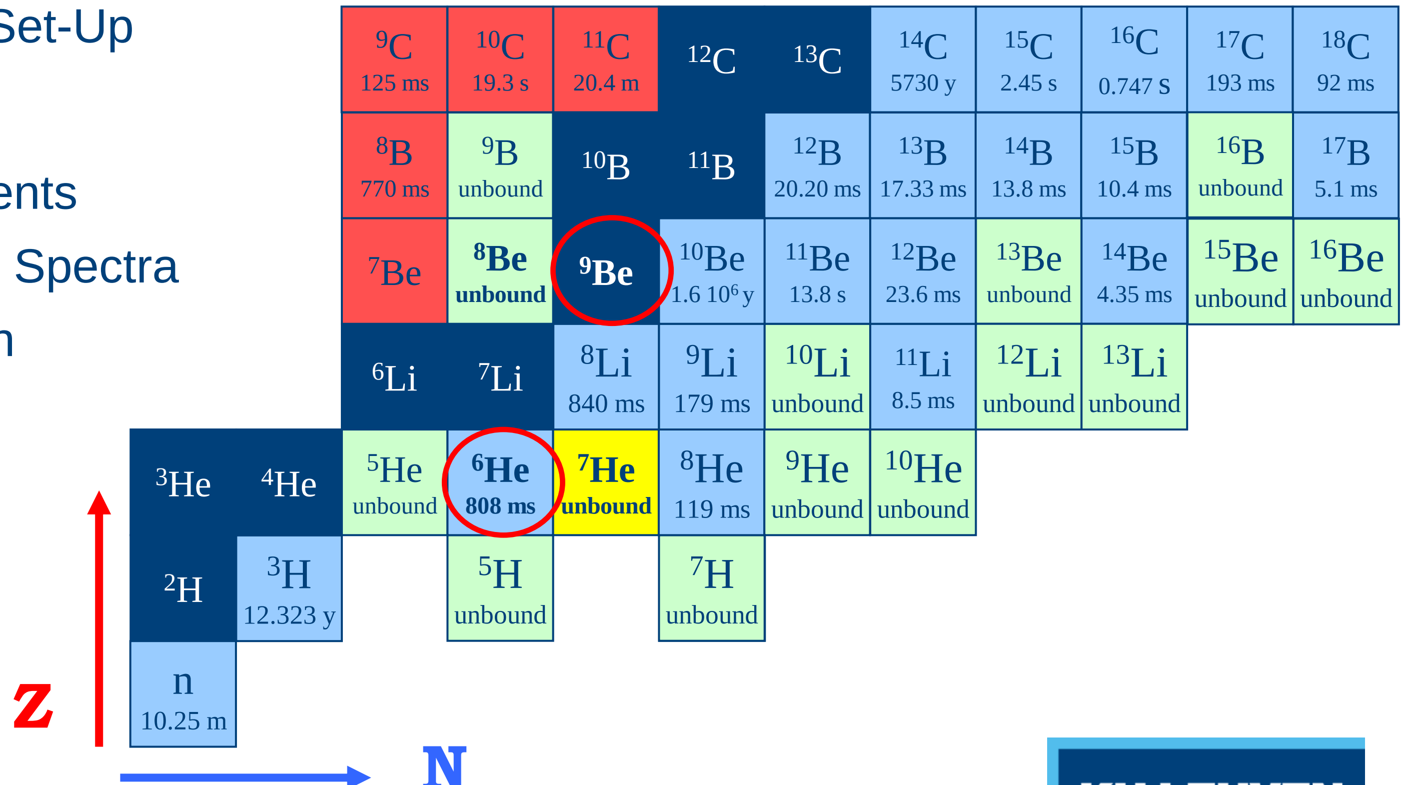
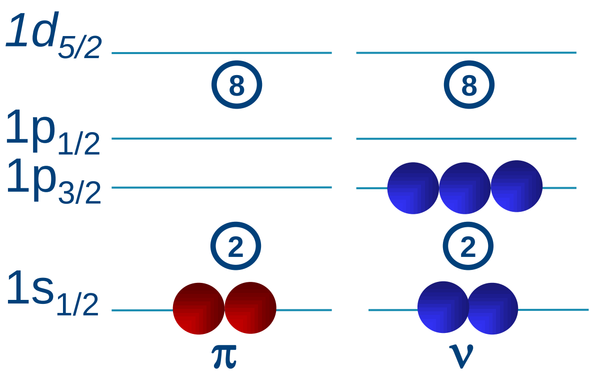
Outline

- ✓ Motivation
- ✓ The measurement at LLN
  - Identification technique
  - Experimental Set-Up
- ✓ Results
  - Coincident Events
  - Reconstructed Spectra
  - ^{7}He Discussion
- ✓ Conclusion



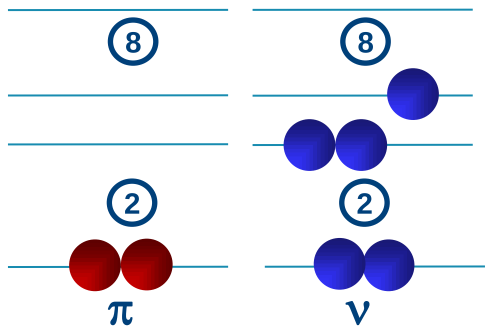
^{7}He: "Make everything as simple as possible…

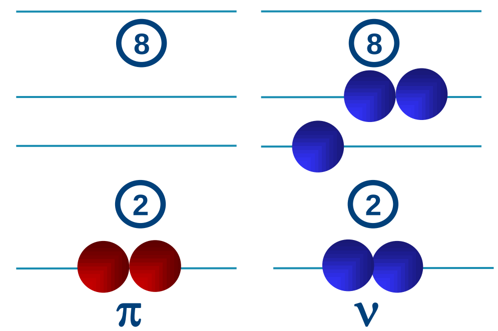


Ground State Configuration $(P_{3/2})^3$

$[|{}^6\mathrm{He}(0^+)\rangle \otimes |\nu 1p_{3/2}\rangle]_{3/2^-}$

$^7\mathrm{He}_{gs} \rightarrow {}^6\mathrm{He} + n$





Configuration $(P_{3/2})^2\,(P_{1/2})^1$

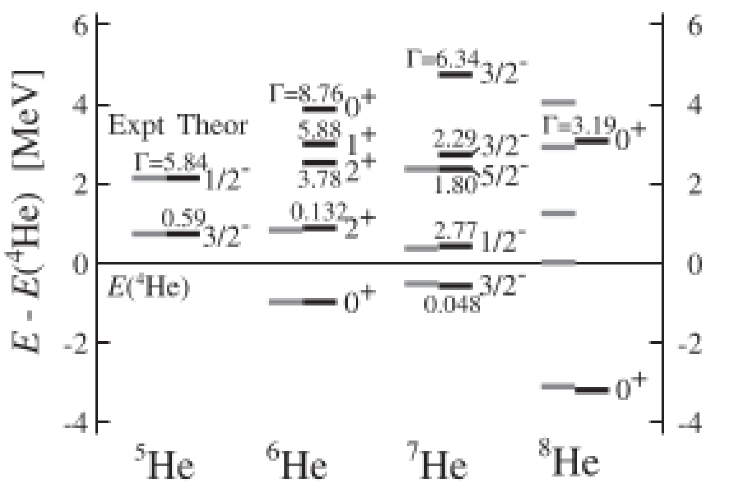
- $J^\pi = 1/2^-$ → $|{}^6\mathrm{He}(0^+)\rangle \otimes |\nu 1p_{1/2}\rangle$ — spin-orbit partner of the ground state → $^7\mathrm{He}^* \rightarrow {}^6\mathrm{He} + n$
- $J^\pi = 3/2^-$
- $J^\pi = 5/2^-$ → $|{}^6\mathrm{He}(2^+)\rangle \otimes |\nu 1p_{1/2}\rangle$ → $^7\mathrm{He}^* \rightarrow {}^4\mathrm{He} + 3n$

Configuration $(P_{3/2})^1(P_{1/2})^2$

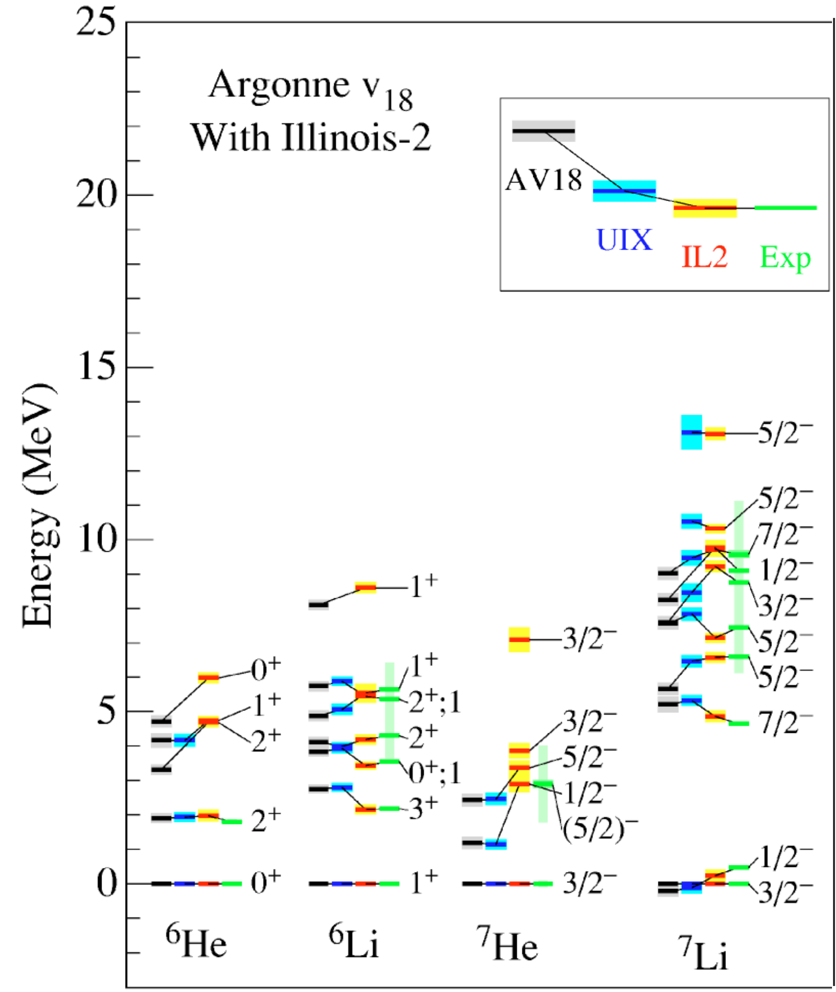
- $J^\pi = 3/2^-$

…but not simpler” A. Einstein

- Predicted sequence: $3/2^-$, $1/2^-$, $5/2^-$, $3/2^-$
- First excited state
  - 2.9(2)MeV Quantum Monte Carlo
  - 1.05MeV COSM + Complex Scaling Method



[Myo *et al.*, PRC 80 (2009)]
[Myo, Progr. Th. Physics 196 (2012)]



[Pieper *et al.*, PRC 70 (2004)]

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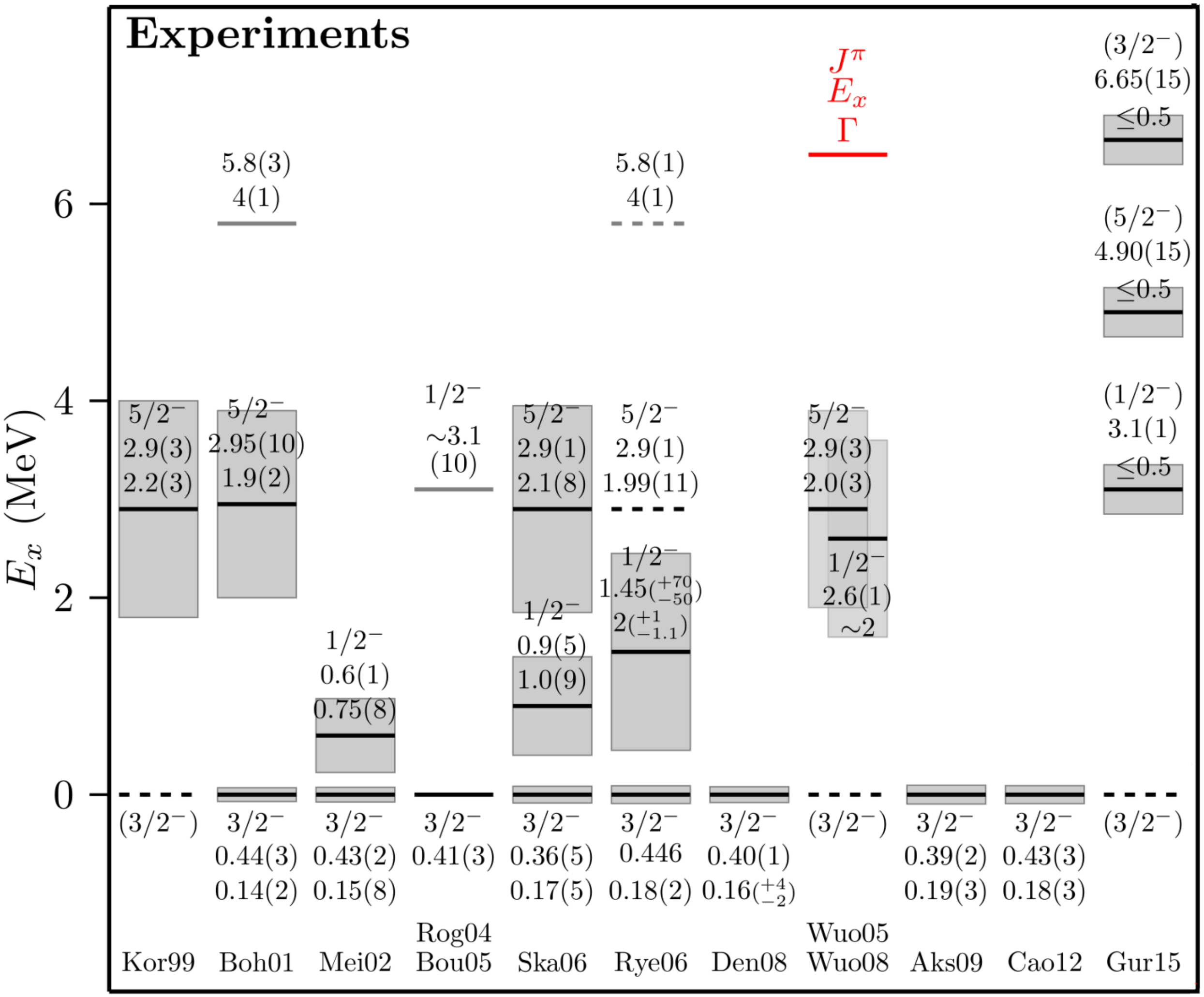
^{7}He: previous experiments



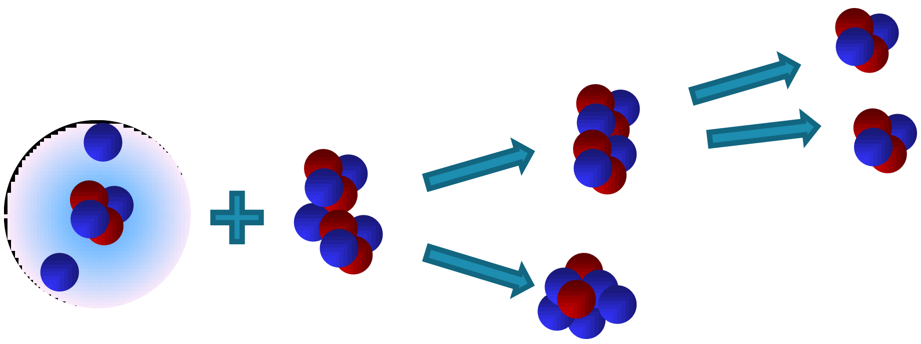
✓Extensively studied nucleus

- More than 30 experiments!
- General agreement on 5/2- state proprieties
- The experimental information about 1/2- state is not conclusive and still controversial.

[Renzi *et al.*, submitted]

Measurement

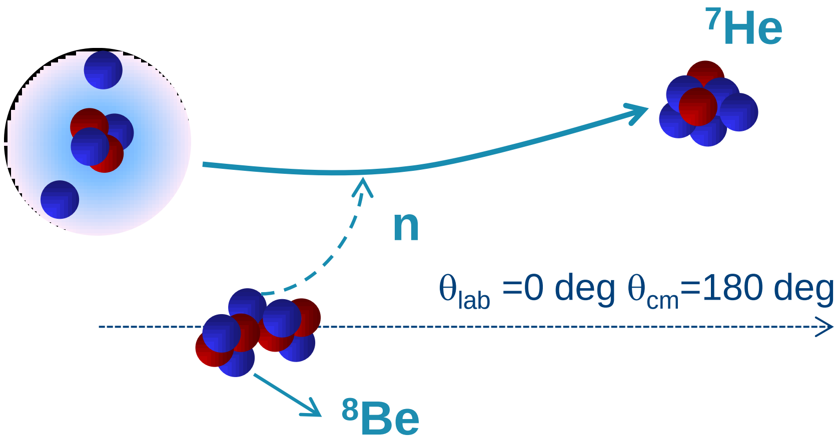
$^{6}He + ^{9}Be \rightarrow ^{8}Be + ^{7}He$



- ✓ Reaction channel identification by $^{8}Be_{gs}$ decay signature
  - $^{8}Be_{gs}$ unstable by 91.8keV for 2α particles decay
  - 2α very close in space and energy
  - *Recently applied to select a candidate resonant tetraneutron state [K. Kisamori al., PRL 116, 2016]*

- ✓ ^{7}He energy spectrum via resonant particle spectroscopy technique

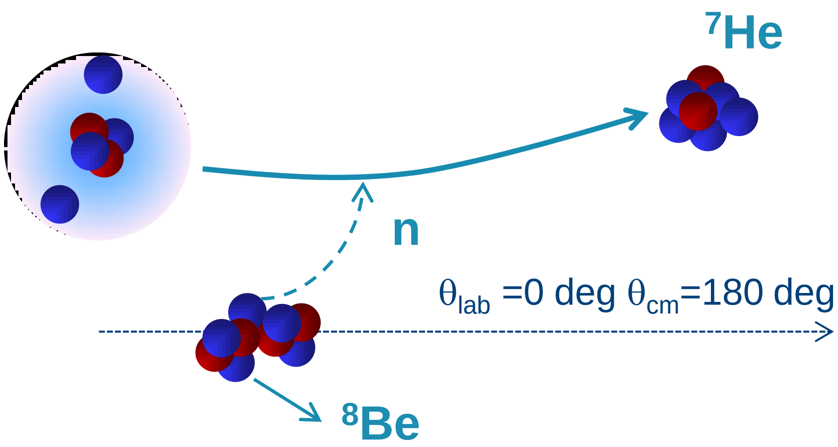
1n pick-up



✓ ^{9}Be(^{6}He,^{7}He)^{8}Be: pick-up of one neutron from ^{9}Be target

- *Weakly bound* ^{9}Be: *S(n) =1.66MeV*
- *Recent direct reaction experimental studies with heavy-mass RIBs [J. M. Allmond et al., PRC 90, 2014]*

1n pick-up || 2p pick-up



- ✓ ^{9}Be(^{6}He,^{7}He)^{8}Be: pick-up of one neutron from ^{9}Be target
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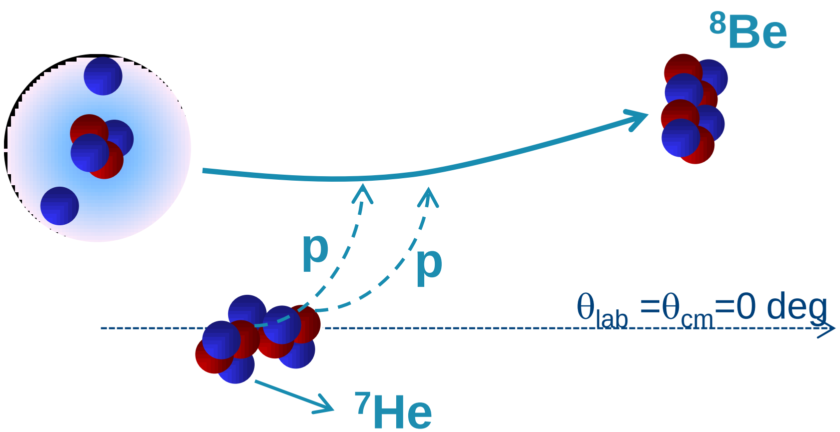
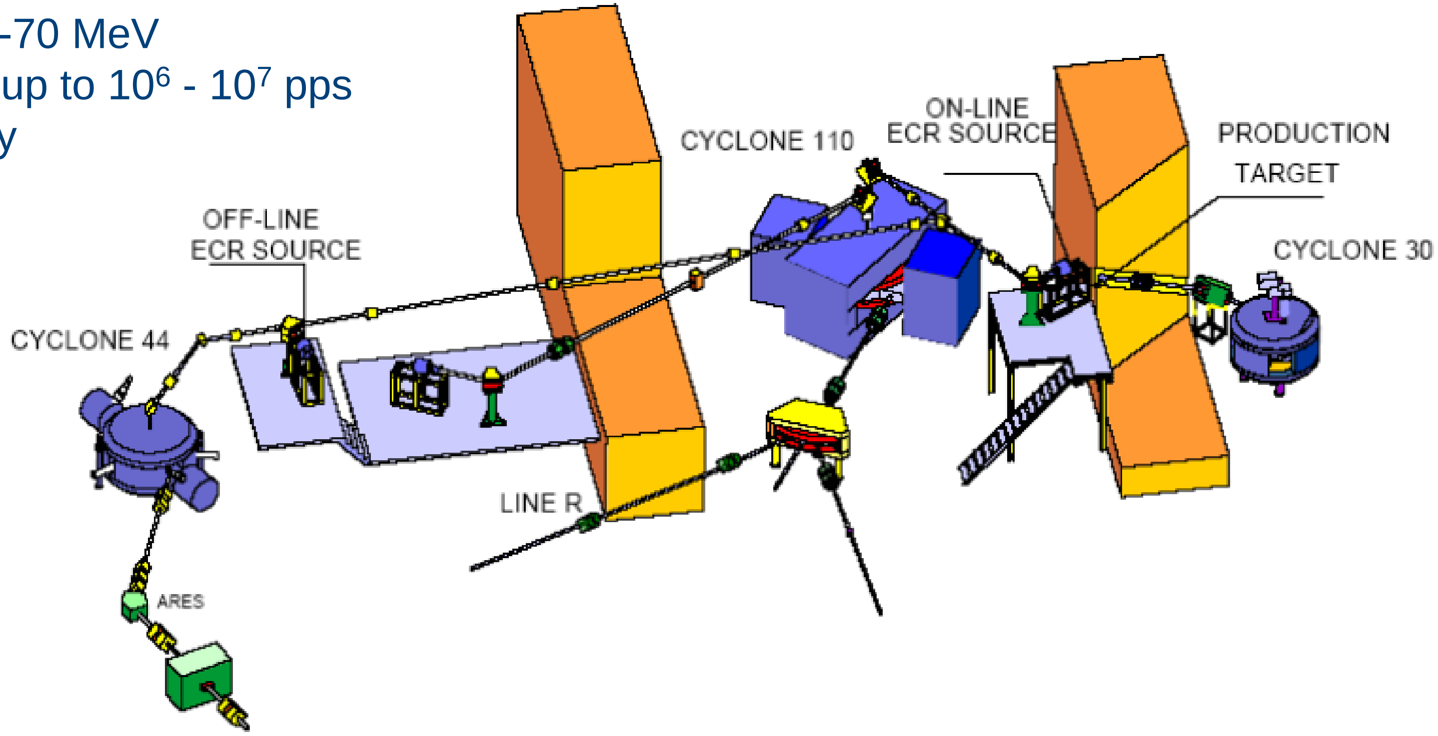


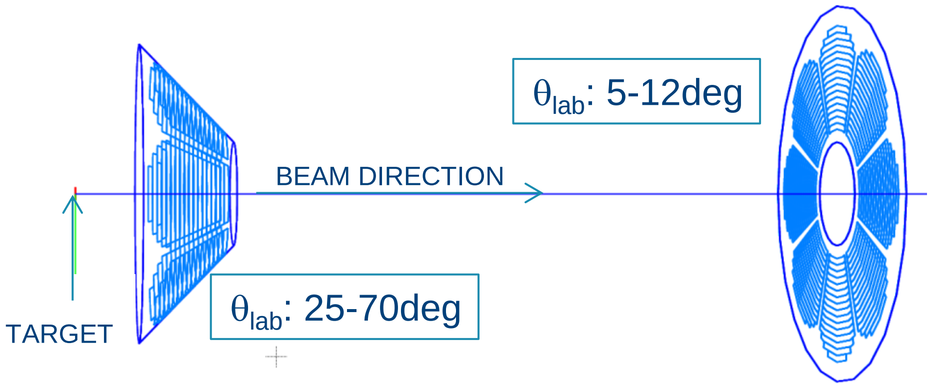
- ✓ ^{9}Be(^{6}He,^{8}Be)^{7}He: pick-up of two protons from ^{9}Be target
  - *"Two-proton pickup reaction (6He,8Be)… on 12C, 16O, and 19F" M. Milin et al., PRC 70, 2004*
  - *"Multi-nucleon transfers using two-neutron halo 6He on 12C at 30 MeV using the SHARC and TIGRESS arrays at TRIUMF ISAC-II" Fr. Sarazin talk, DREB2012*

Louvain-la-Neuve facility

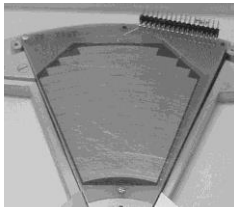
- ✓ Two cyclotrons
- ✓ Primary beam: protons @30 MeV
- ✓ Production reaction: $^{7}Li(p,2p)^{6}He$
- ✓ Secondary beam (^{6}He):
  - energy: 5-70 MeV
  - intensity: up to 10^6 - 10^7 pps
  - high purity



Detection Set-up @LLN

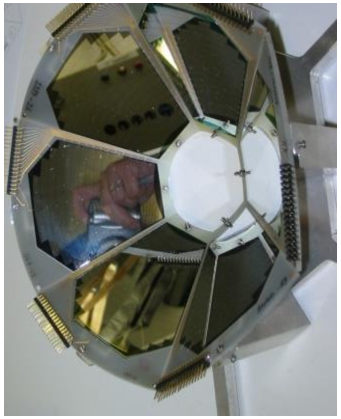


16 strips
300μm thick

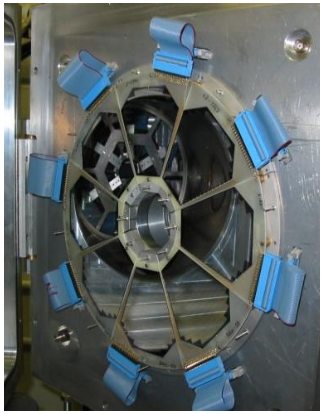


✓Targets:
^{9}Be 394μg/cm^{2}
^{197}Au 200μg/cm^{2}

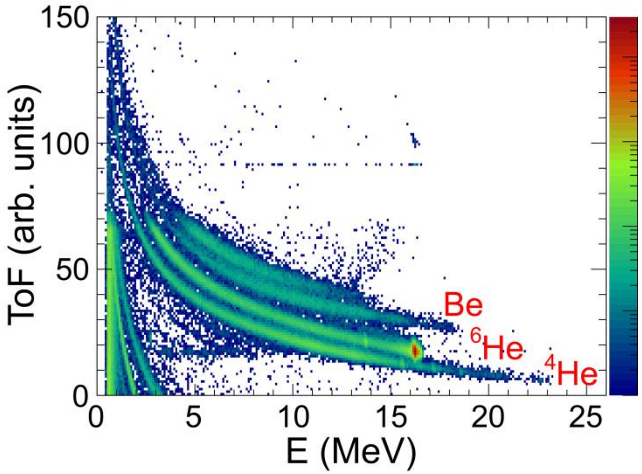
✓Used beams ^{6}He,^{6}Li
E_{lab}~16.8MeV



LAMP
6 sectors
$\Delta\theta \sim 3.06°$
$\Delta\phi \sim 45°$

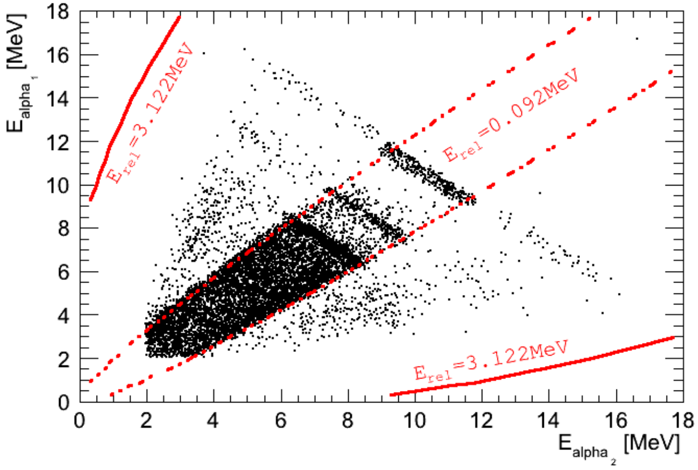


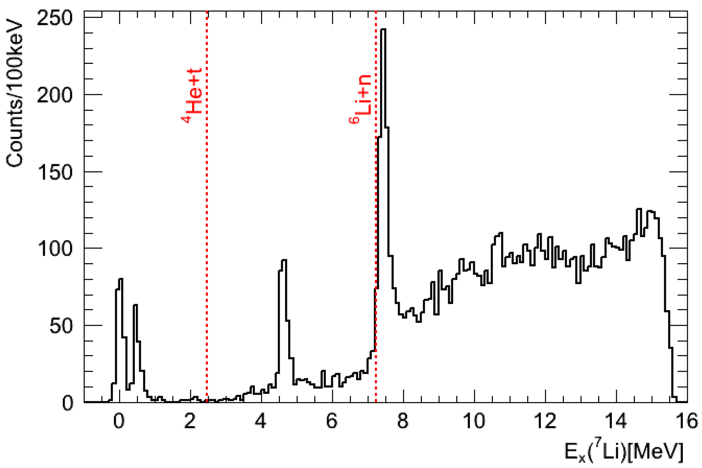
LEDA
8 sectors
$\Delta\theta \sim 0.48°$
$\Delta\phi \sim 45°$



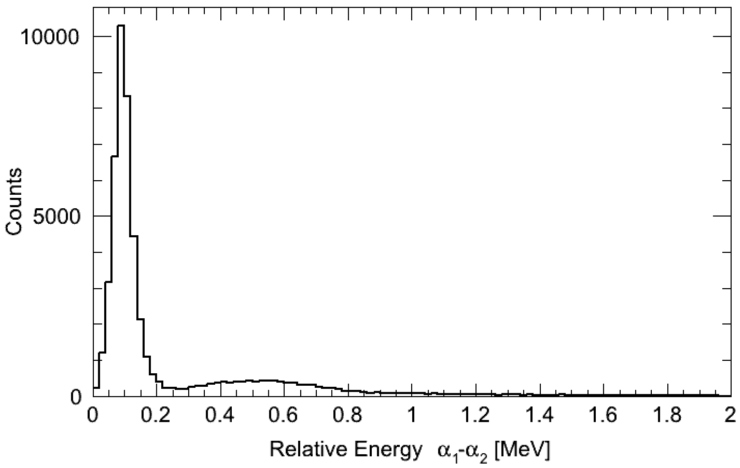
Results: $^9Be(^6Li,^7Li)^8Be$

✓ 2α Coincident events in LEDA



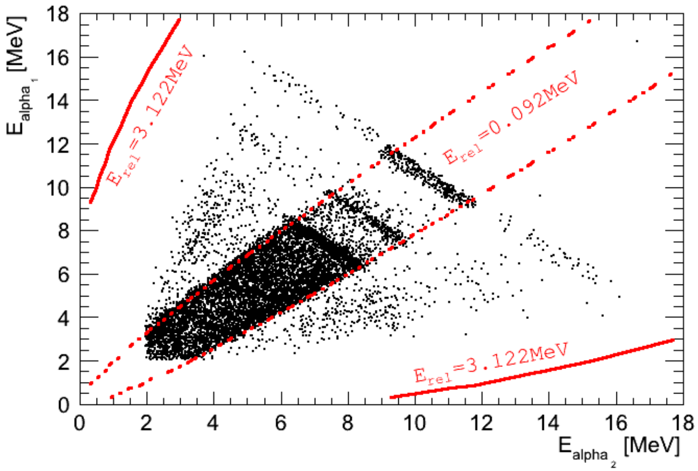


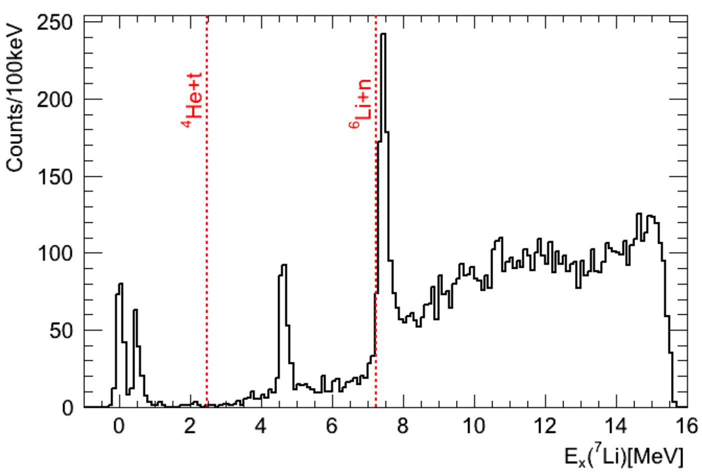
✓ Decay energy of $^8Be_{gs}$



Results: $^{9}Be(^{6}Li,^{7}Li)^{8}Be$

✓2α Coincident events in LEDA



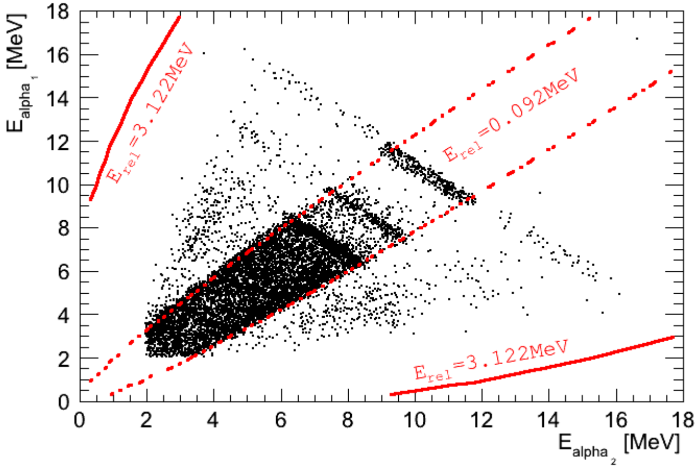


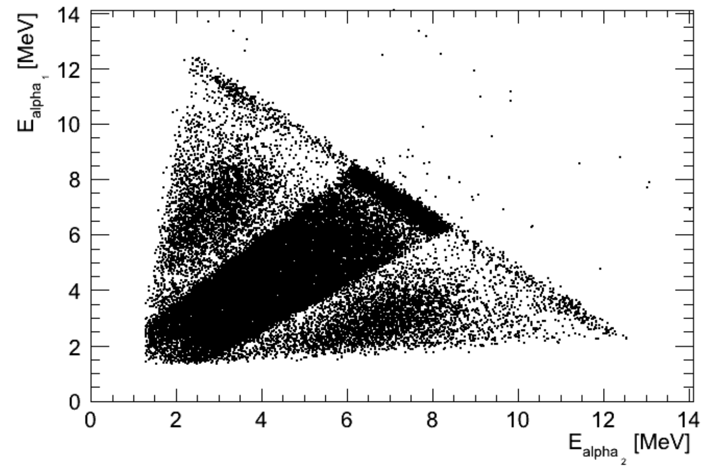
✓^{7}Li spectrum, firm identification of four states

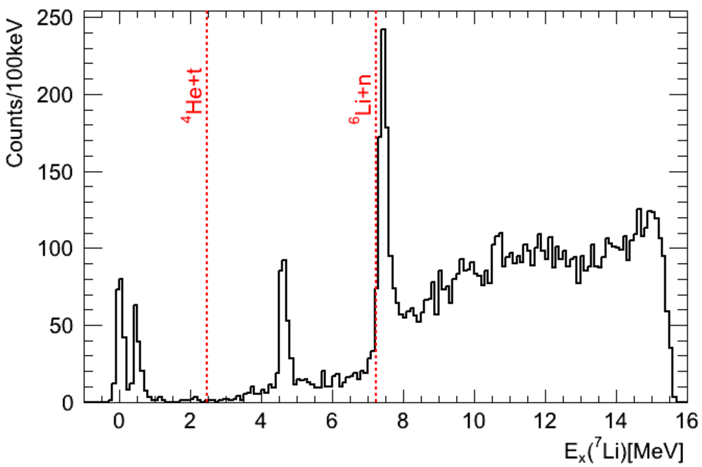
E_x (MeV ± keV)	$J^\pi; T$	τ_m or Γ_{cm} (keV)	Decay
g.s.	$\frac{3}{2}^-; \frac{1}{2}$		stable
0.477612 ± 0.003	$\frac{1}{2}^-; \frac{1}{2}$	$\tau_m = 105 \pm 3$ fsec [a]	γ
4.652 [b]	$\frac{7}{2}^-; \frac{1}{2}$	$\Gamma = 69$ keV [b]	t, α
6.604 [b]	$\frac{5}{2}^-; \frac{1}{2}$	918 [b]	t, α
7.454 [b]	$\frac{5}{2}^-; \frac{1}{2}$	80 [b]	n, t, α
8.75 [b]	$\frac{3}{2}^-; \frac{1}{2}$	4712 [b]	n, α
9.09 [b]	$\frac{1}{2}^-; \frac{1}{2}$ [b]	2752 [b]	n, t, α
9.57 [b]	$\frac{7}{2}^-; \frac{1}{2}$	437 [b]	n, t, α
11.24 ± 30	$\frac{3}{2}^-; \frac{3}{2}$	260 ± 35	n, p

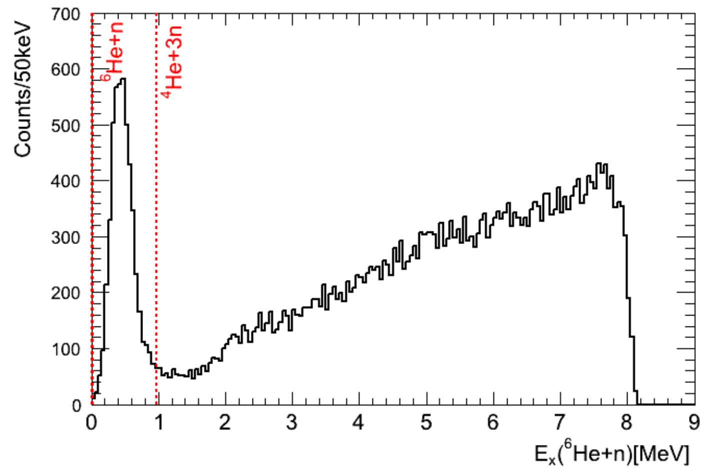
Nucl. Phys. A708 (2002)

$^{6}Li+^{9}Be\rightarrow^{7}Li+^{8}Be$ $^{6}He+^{9}Be\rightarrow^{7}He+^{8}Be$

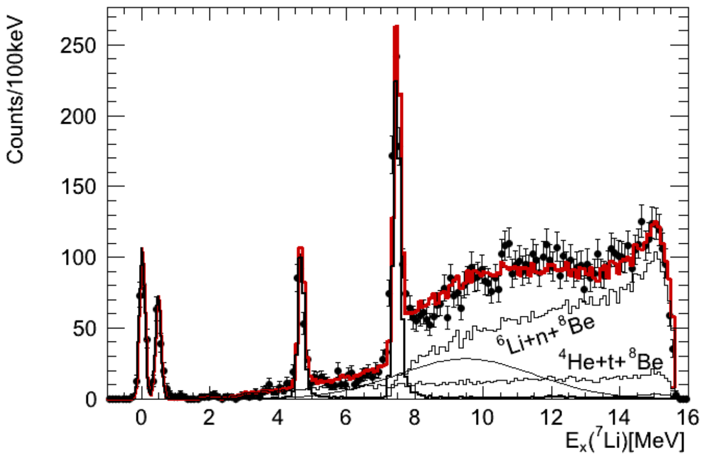








$^{6}Li+^{9}Be \rightarrow ^{7}Li+^{8}Be$



→ ^{7}Li resonances

- *R-matrix*

E and Γ from literature

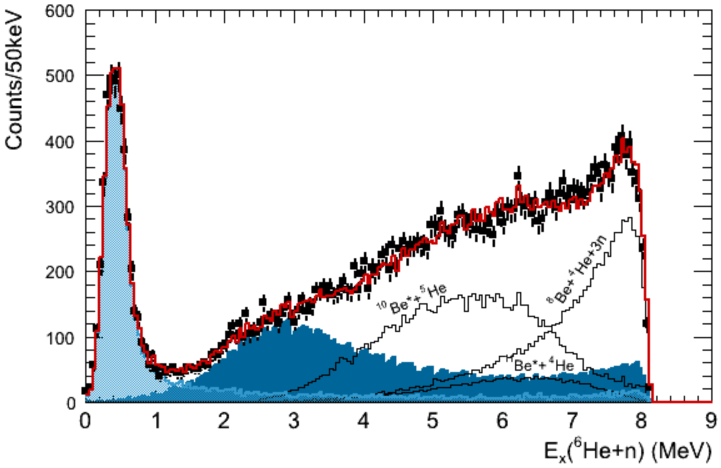
→ Background contributions

- *phase space contributions*

Geant4 simulation

simulated events and experimental data have been analyzed exactly in the same way

$^{6}He+^{9}Be \rightarrow ^{7}He+^{8}Be$



→ ^{7}He resonances

- *R-matrix*

E and Γ vary in a range of values

→ Background contributions

- phase space contributions
- other reaction channels
  1(2)-neutron(s) transfer reaction
  M. Majer *et al*,. Eur. Phys. J. A **43** (2010)

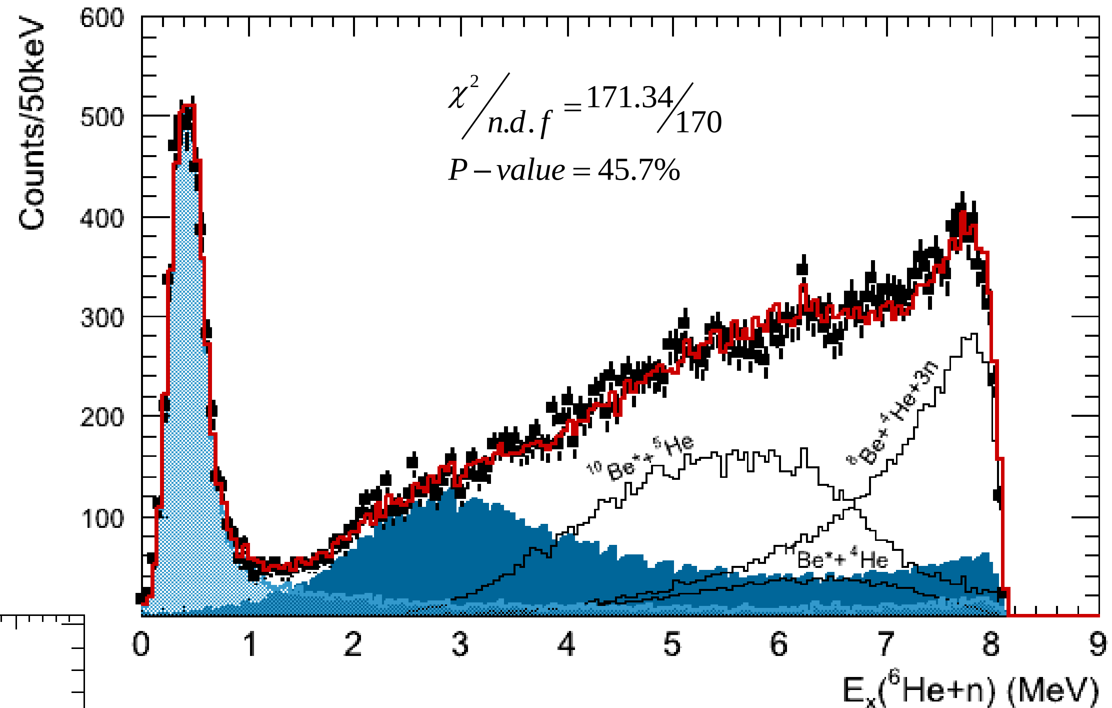
Results: ^{7}He spectrum

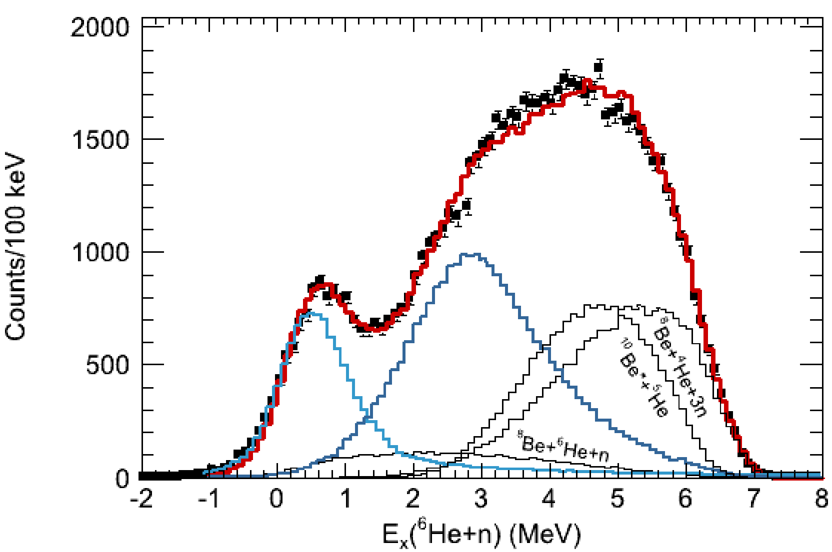
✓ Ground State:

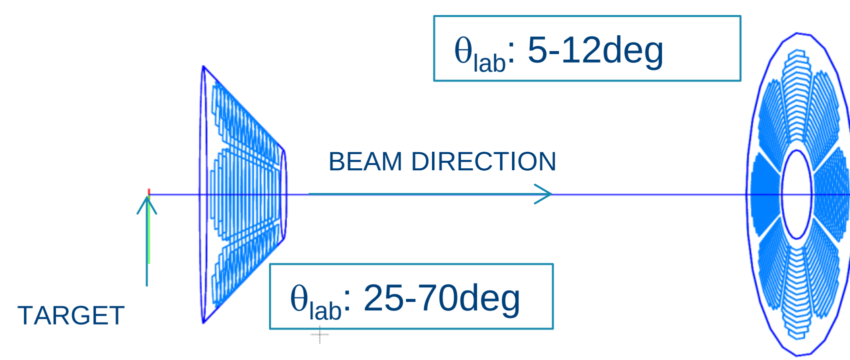
- E_{gs} = 380(28) keV
- Γ = 179(21) keV
- γ^2_{obs} = 0.915(20) MeV (l=1)

✓ Excited state:

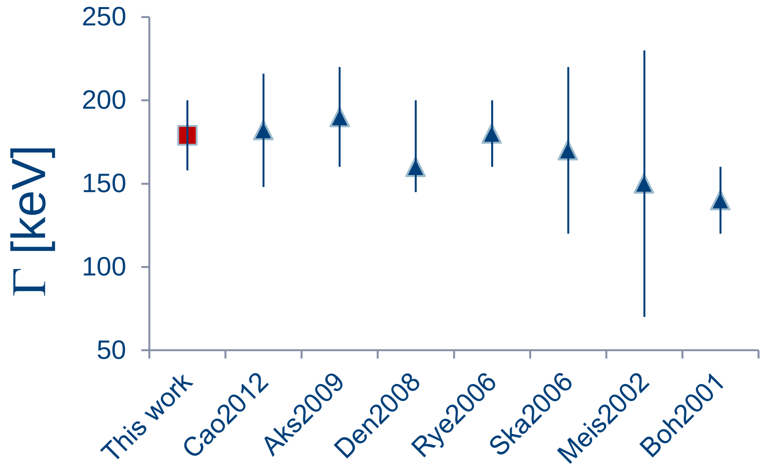
- E_{ex} = 2.6(2) MeV
- Γ_{FWHM} = 2.3(3) MeV
- γ^2_{obs} = 1.586(120) MeV (l=1)

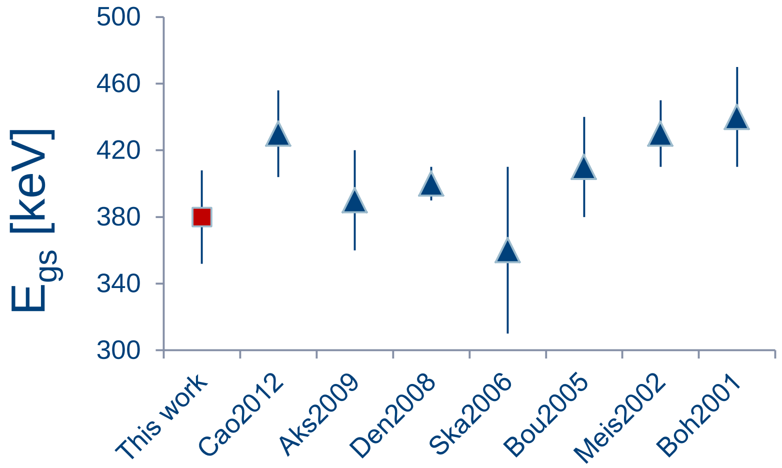






Results: ^{7}He ground state





Spectroscopic factor

^{7}He(J^π)	^{6}He-n(l_j)	CSM	GFMC	NCSM	Exp	
$3/2^-_1$	0^+ - $p_{3/2}$	0.64	0.565	0.56	**0.61(2)*** 0.512(18)* 0.619(22)* 0.64(9)** 0.37(7)	**This work** PLB 707 (2012) PLB 679 (2009) PLB 645 (2007) PRC 78 (2008)

* γ^2_{sp} = 1.504(29) MeV
** γ^2_{sp} = 1.748 MeV

R = 4fm

[Baroni *et al.*, PRL 110 (2013)] [Brida *et al.*, PRC 84 (2011)]

Results: ^{7}He excited state

✓Excited state:

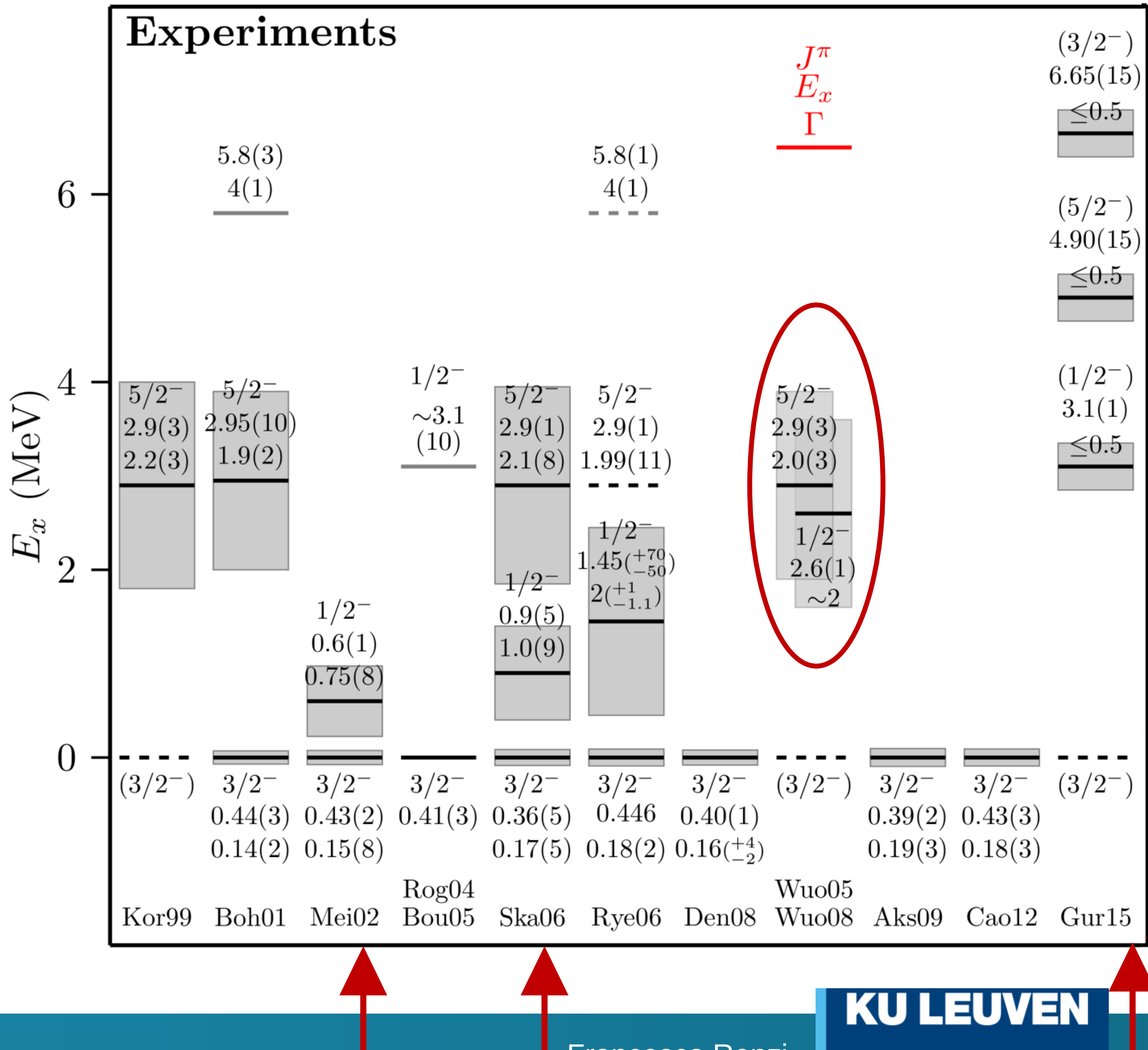
- E_{ex} = 2.6(2) MeV
- Γ_{FWHM} = 2.3(3) MeV
- γ^2_{obs} = 1.586(120) MeV (R=4fm l=1)

✓Excellent agreement with the d(^{6}He,p) results

[Wuo05:PRC 72 (2005)]

✓Upper limits:

- Ska06 [PRC 73 (2006)]: any contribution bigger than 3.4% of ground state can be rule out at 99%CL
- Mei02 [PRL 88 (2002)]: any contribution bigger than 4% of ground state can be rule out at 99%CL



Results: ^{7}He excited state… 1/2^{-} or 5/2^{-}?

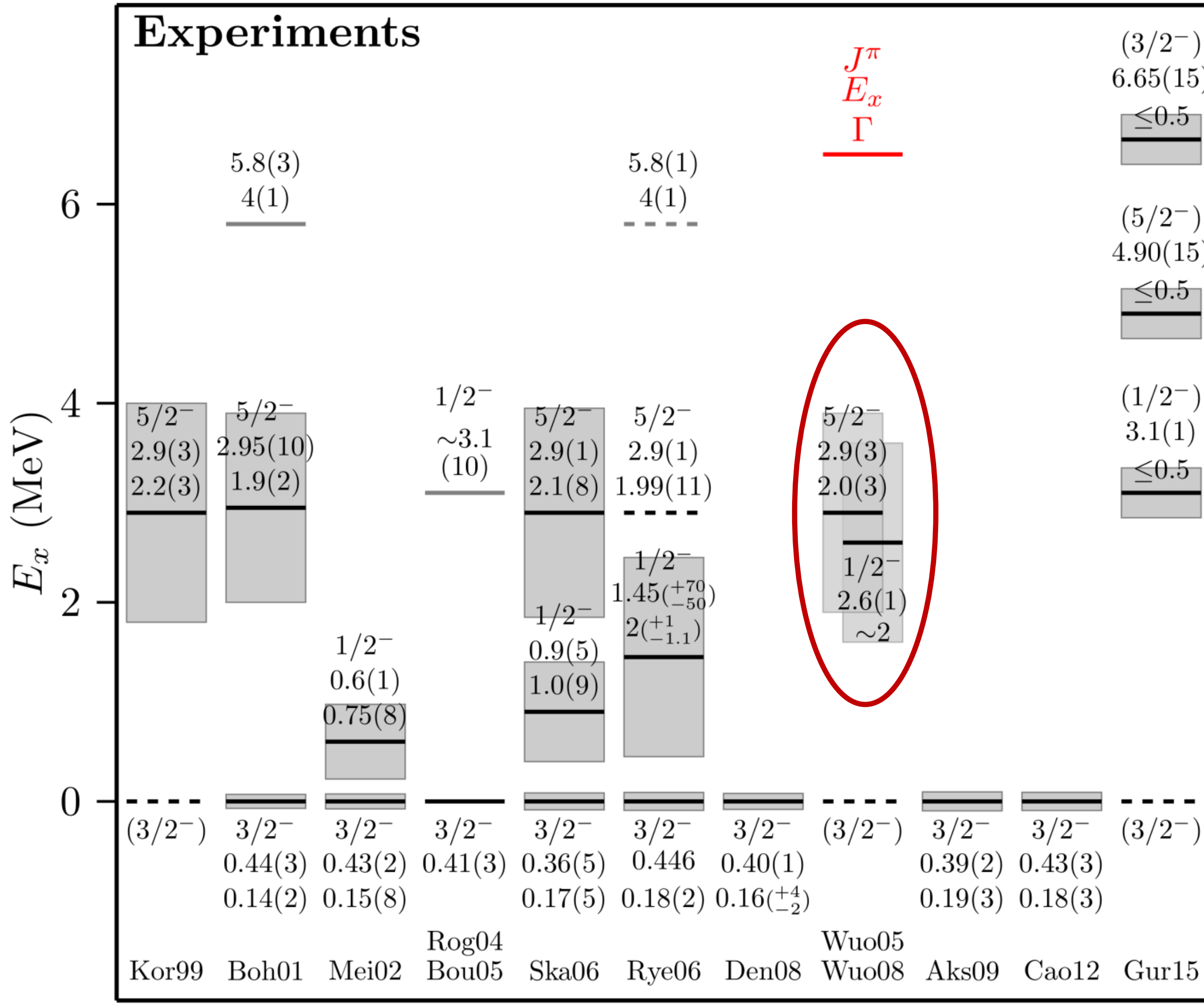
✓ Excited state:

- E_{ex} = 2.6(2) MeV
- Γ_{FWHM} = 2.3(3) MeV
- **γ^2_{obs} = 1.586(120) MeV (R=4fm l=1)**

✓ **Excellent agreement with the d(^{6}He,p) results [Wuo05:PRC 72 (2005)]**

✓ **1-n pick-up would favor the ^{6}He$_{gs}$ ⊗ n configurations**

✓ **No info on the charged particle from ^{7}He decay (^{6}He or ^{4}He)**



Conclusion

^{7}He nucleus has been investigated using a new reaction

- ^{7}He ground state: E, Γ and SF are consistent with the recent results
- ^{7}He excited state: E, Γ in vey good agreement with d(^{6}He,p) reaction

The very clear signature of $^{8}Be_{gs}$ decay confirms its advantages as reaction channel identification technique

Question time

Previous work

					E_{gs}	Γ	S_n	E_{ex}	Γ	E_{ex}	Γ	E_{ex}	Γ	E_{ex}	Γ	E_{ex}	Γ	E_{ex}	Γ
Gurov 2015	10B(π−,dd); 11B(π−,pt); 11B(p-,dd);	30MeV	LAMPFmeson facility	10B and 11B				3,1(1)	<=0,5	4,9(15)	<=0,5	6,65(15)	<=0,5	16,9(5)	1(0.3)	19,8(3)	1,5(3)	24,8(4)	4,6(7)
Cao 2012	8He recoil p tagged knockout	82,3MeV/u	RIPS @RIKEN	hydrogen and carbon target	0,430(26)	0,182(31)	0,512(18)												
Aksyutina 2009	8He n knockout	240MeV/u	ALADIN-LAND @GSI	lyquid-hydrogen target	388(20)	190(30)	0,61(3)												
Wousmaa2008	8Li (d,3He) p removal	76MeV	"in-flight" RIB @ATLAS	(CD2)n	**observed**	**observed**		2,9(3)	2,0(3)										
Denby 2008	8Li p knockout	41MeV/u	MONA @NSCL	9Be	0,400(10)	0,160(+40-15)													
Ryezayeva 2006 Beck2007	7Li(d,2He) charge exchange	171MeV	AGOR Cyclotron KVI	7Li	0,446	183(22)	0,64	1,45(+0,7-0,5)	2(+1,0-1,1)	**2,9(1)**	**1,99(11)**	**5,8(3)**	**4(1)**						
Skaza2006	p(8He,d)	15,7MeV/u	SPIRAL MUST	(CH2)n	0,36(5)	0,17(5)		0,9(5)	1,0(9)	2,9(1)	2,1(8)								
Wousmaa2005	6He(d,p)7He	11,5MeV/u	"in-flight" RIB @ATLAS	(CD2)n	**observed**	**observed**	0,37(7)	2,6(1)	~2										
Boutachkov 2005 Rogachev2004	6He+p→7Li-IAS of 7He →6Li0++n	0-24MeV	TwinSol @Notre Dame	(CH2)n	0,41(3)			3,1	broad(10)										
Meister 2002	8He n knockout	240MeV/u	ALADIN-LAND @GSI	carbon	0,43(2)	0,15(8)		0,6(1)	0,75(8)										
Bohlen 2001	(15N,17F)	240MeV 318,5MeV	HMI	9Be	0,44(3)	0,14(2)		2,95(10)	1,9(2)	5,8(3)	4(1)								
korsheninnikov 1999	p(8He,d)	50MeV/u	RIPS @RIKEN	CH2 C	**observed**	**observed**		2,9(3)	2,2(3)										

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