

# Unbound Nuclei Workshop

Pisa, 3-5 November 2008

Beyond the dripline: an outlook

*Jim*





# Experimental Studies of Unbound Nuclei

- **Experimental filter**

Acceptance, resolution, efficiency

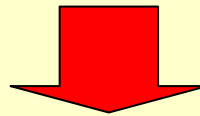
- **Structure of projectile and target**

Clusterisation, spin

- **Reaction Mechanism and projectile energy**

Knockout, transfer, inelastic scattering, models

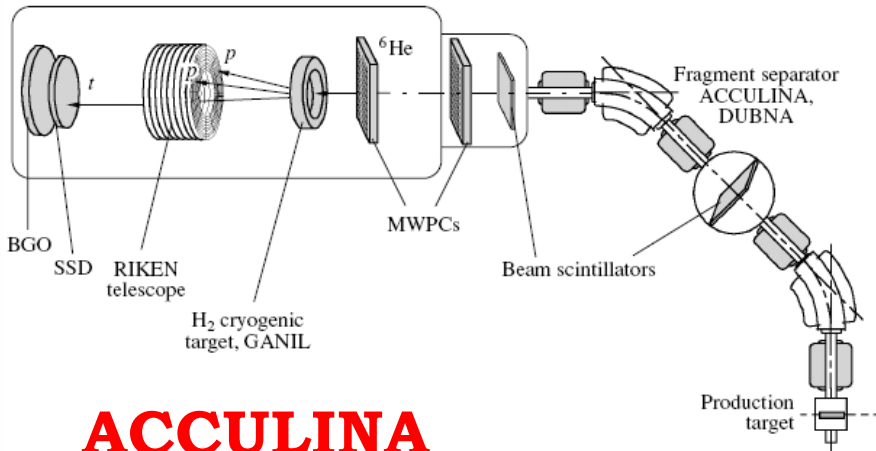
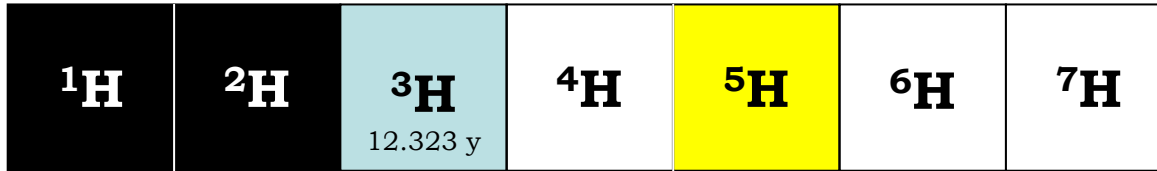
- **Final State Interactions in the Continuum**



Cross sections, scattering length,  
angular distributions, resonance  
energies and widths, energy and  
angular correlations

# Superheavy Hydrogen $^5\text{H}$

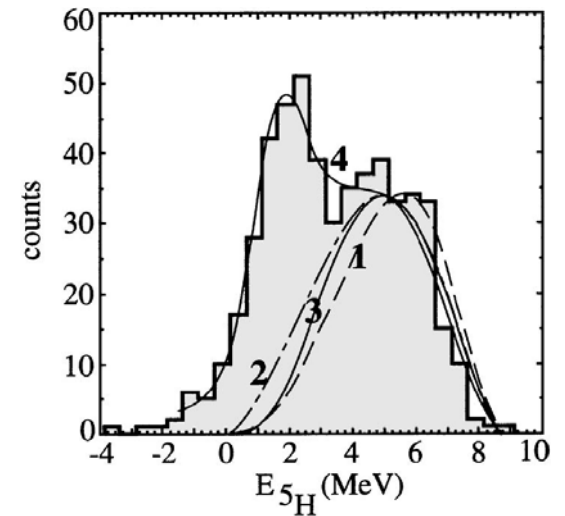
A.A. Korshennikov et al., PRL 87(2001) 092501



**ACCULINA**

$^6\text{He}$  (36 MeV/u)

$p(^6\text{He}, pp)^5\text{H}$



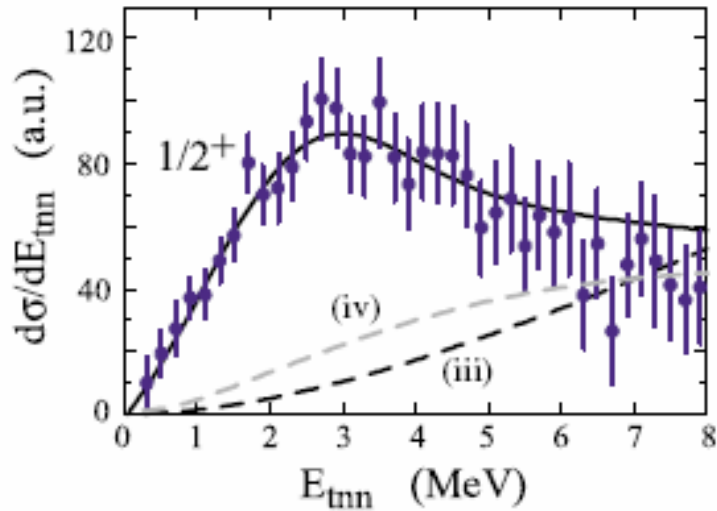
$E_R = 1.7(3)$  MeV above  $(n + n + t)$   
 $\Gamma = 1.9(4)$  MeV



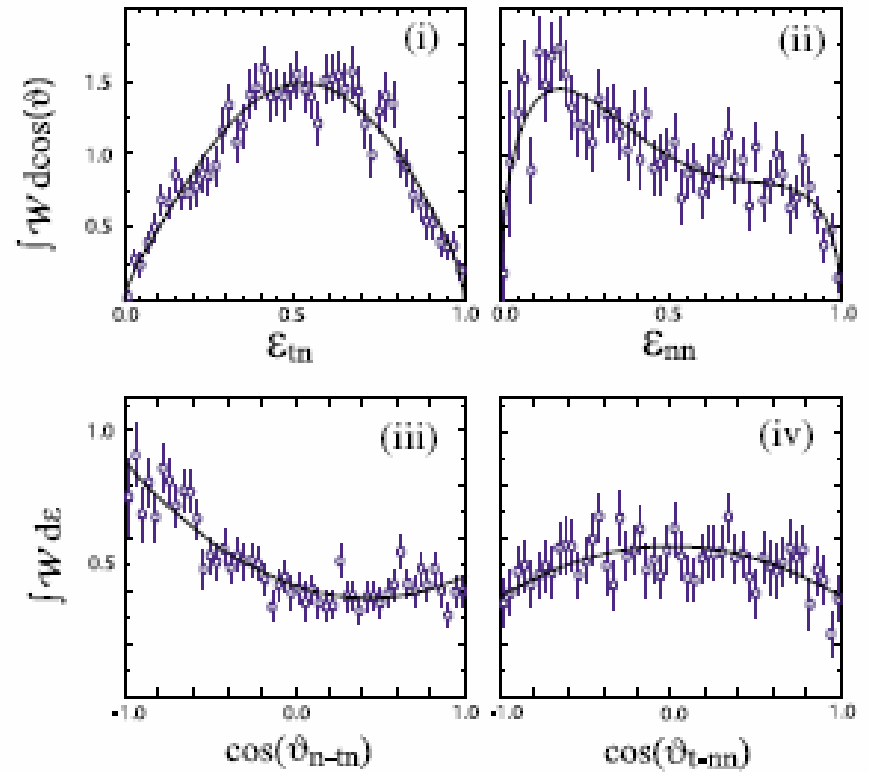
## The $t + n + n$ System and ${}^5\text{H}$

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

GSI,  ${}^6\text{He}$  (240 MeV/u)



N.B. Shul'gina *et al.*, PRC 62 (2000) 014312



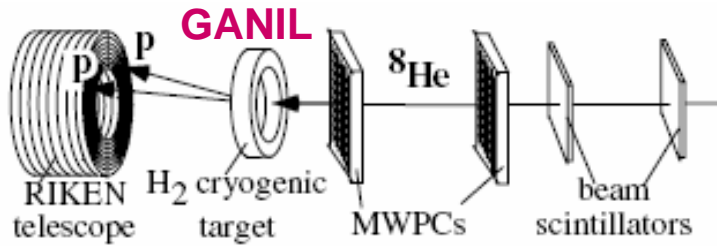


$^1\text{H}$	$^2\text{H}$	$^3\text{H}$ 12.323 y	$^4\text{H}$	$^5\text{H}$	$^6\text{H}$	$^7\text{H}$
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A.A. Korshennikov et al., PRL 90(2003) 082501

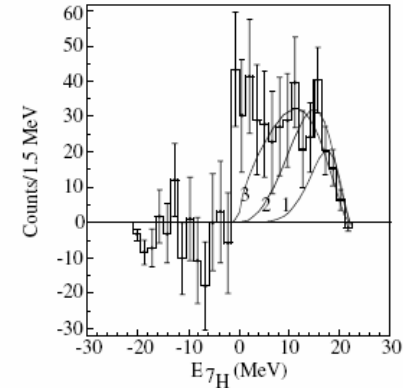
**RIKEN**

$^8\text{He}$  @ 61.3/MeV/u

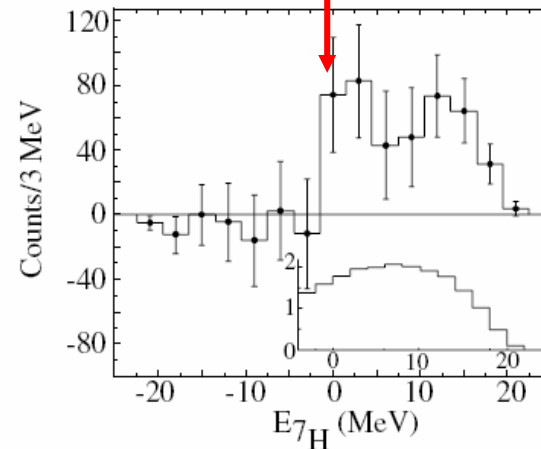


$p(^8\text{He}, pp)^7\text{H}$

$d(^8\text{He}, ^3\text{He})^7\text{H}$   
 $t(^8\text{He}, ^4\text{He})^7\text{H}$



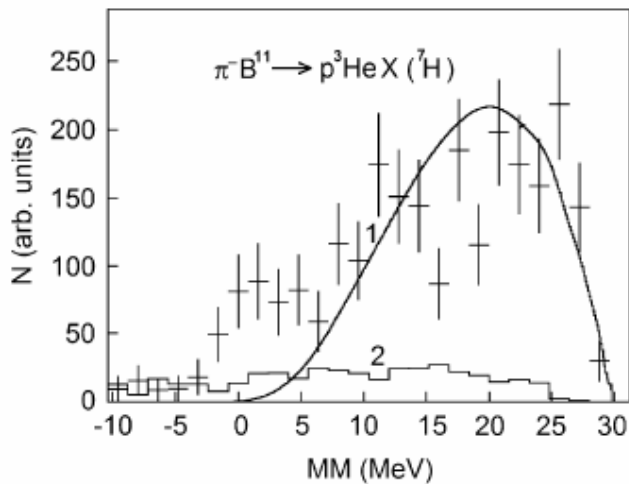
$t + 4n$



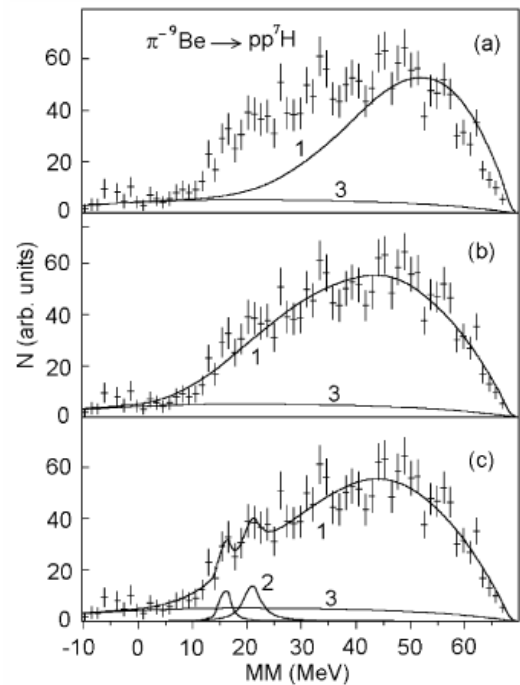


# $\pi^-$ – absorption reactions

Yu. B. Gurov et al., Eur. Phys. J. A 32 (2007) 261



Low-Energy Pion channel at LAMPF





# <sup>7</sup>H

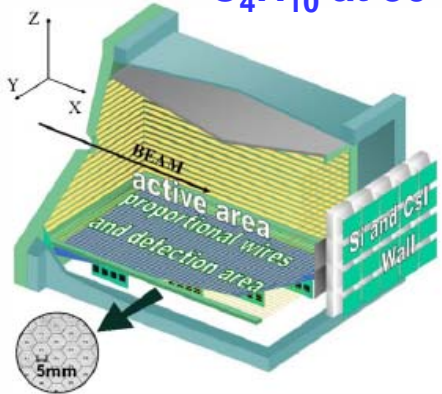


## Resonance State in <sup>7</sup>H

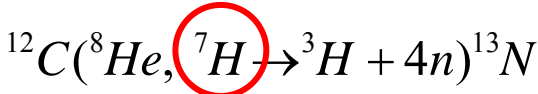
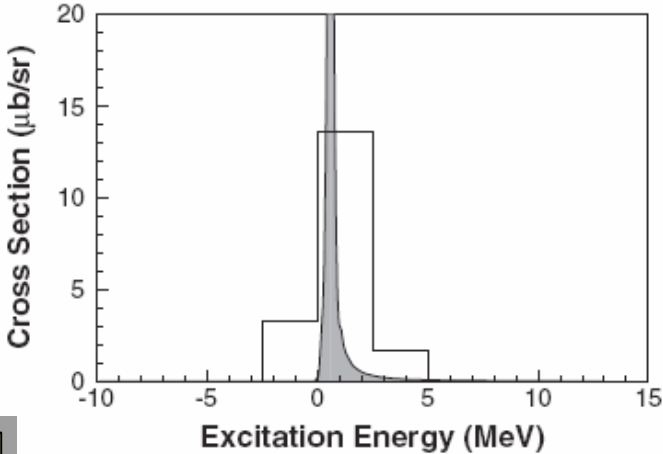
M. Caamaño et al., PRL 99 (2007) 062502

M  
A  
Y  
A

C<sub>4</sub>H<sub>10</sub> at 30 mbar



$$\sigma_{BW} = \sigma_0 \frac{\Gamma \sqrt{E^{exc} / E_R}}{(E^{exc} - E_r)^2 + (\Gamma^2 / 4)(E^{exc} / E_R)}$$

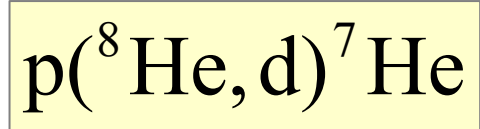


$\Gamma = 0.09^{+0.94}_{-0.06} \text{ MeV}$   
 $E_R = 0.57^{+0.42}_{-0.21} \text{ MeV}$

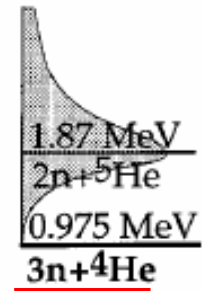
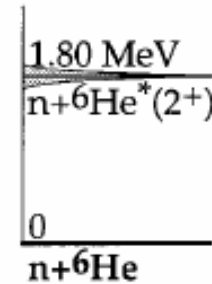
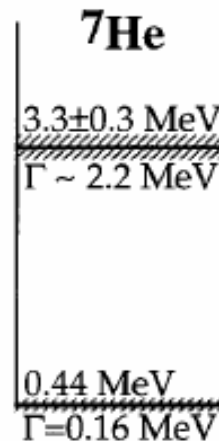
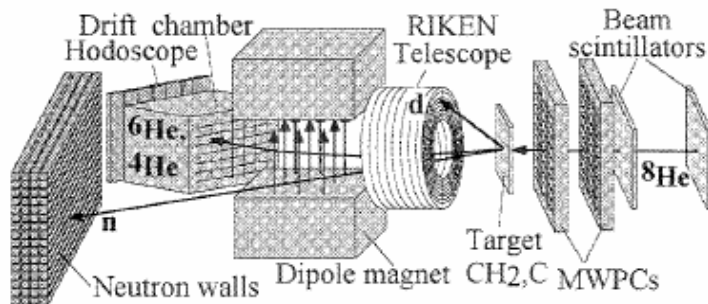
**SPIRAL**  
**<sup>8</sup>He @ 15.4 MeV/u**

${}^6\text{He}$ 806 ms	${}^7\text{He}$ $p_{3/2}$	${}^8\text{He}$ 119 ms	${}^9\text{He}$	${}^{10}\text{He}$
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A.A. Korshennikov et al., PRL 82(1999) 3581

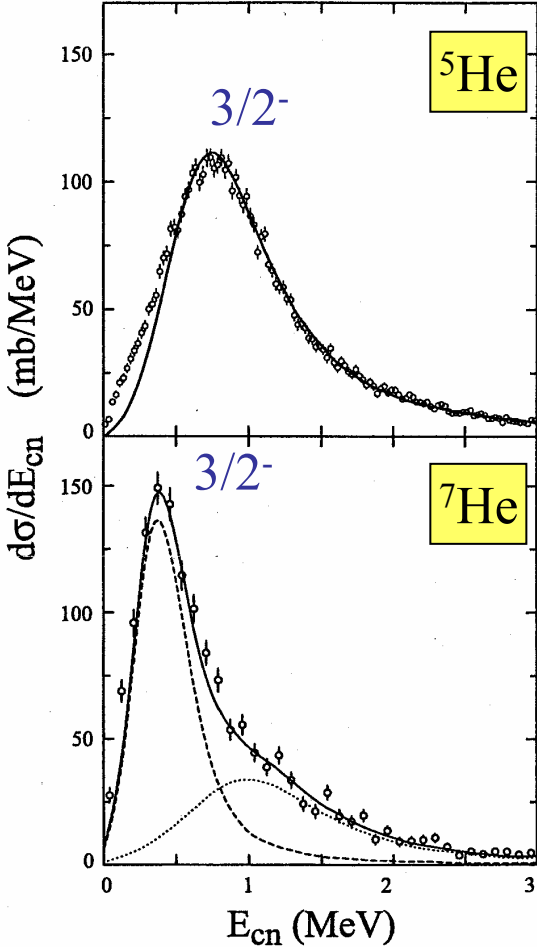


$E^* = 2.9(3) \text{ MeV}$   
 $\Gamma = 2.2(3) \text{ MeV}$



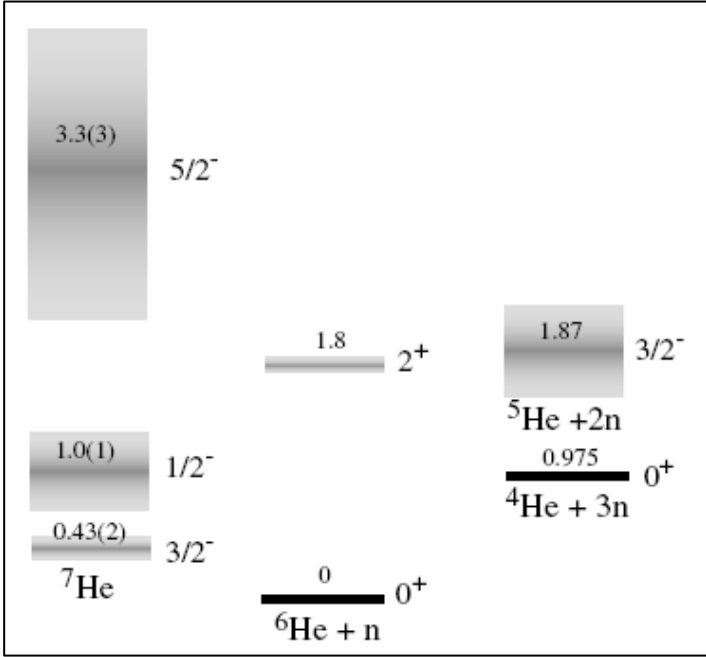
# <sup>7</sup>He

Carbon target



<sup>6</sup>He

227 MeV/u,  
<sup>8</sup>He  
 FRS/ALADIN/LAND  
 GSI



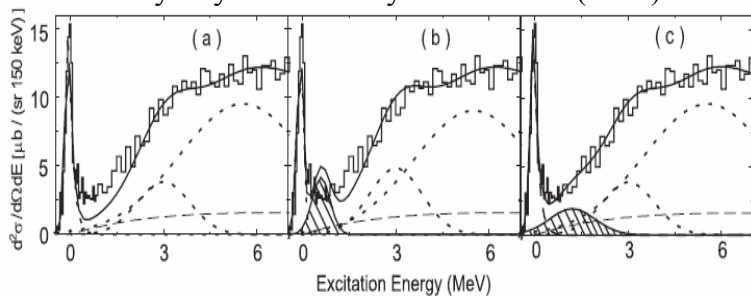
M. Meister et al., PRL 88 (2002) 102501

K. Markenroth et al., Nucl. Phys. A679 (2001) 462

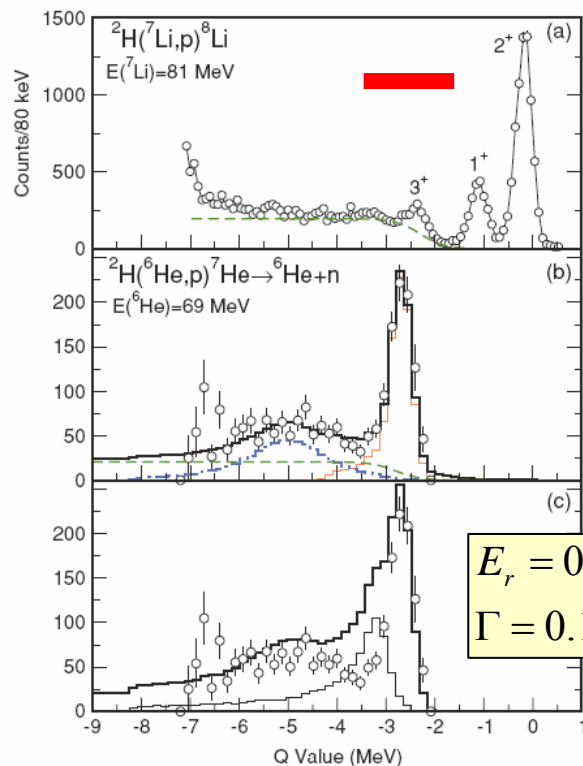
AGOR, 171 MeV d  
 ${}^7\text{Li}(d, {}^2\text{H})$

${}^6\text{He}$ 806 ms	${}^7\text{He}$ $p_{3/2}$	${}^8\text{He}$ 119 ms	${}^9\text{He}$	${}^{10}\text{He}$
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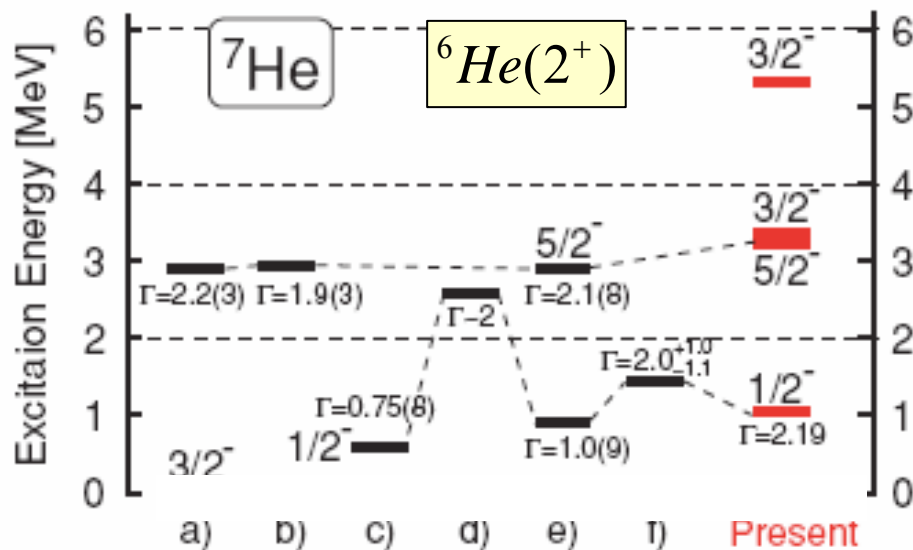
N. Ryezayeva et al. Phys. Lett. B639 (2006)623



ATLAS, Argonne  
 ${}^6\text{He}(d, p)$



A.H. Wuosmaa et al. PR C72 (2007)061301(R)

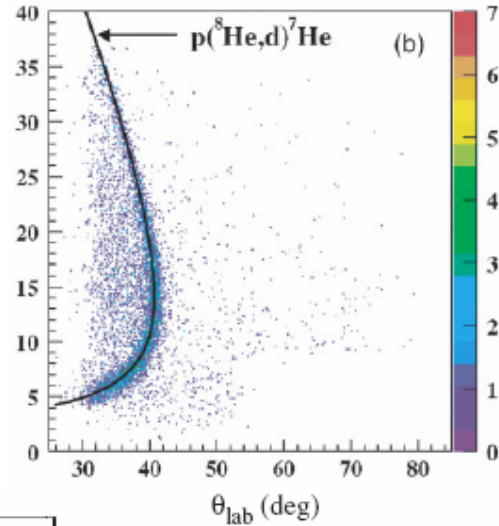
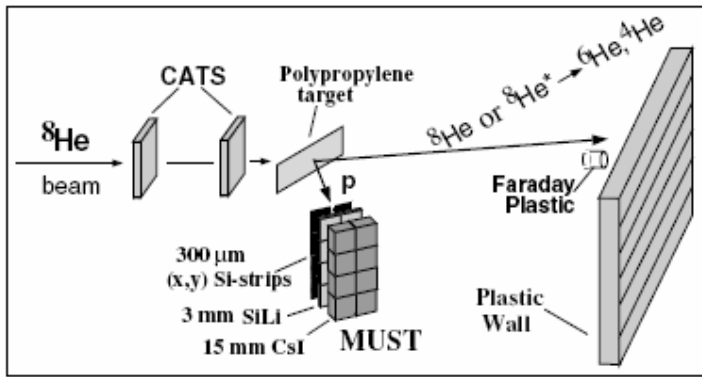


Myo, Katō, Ikeda, PRC 76(2007)054309

Pisa Workshop, 2008

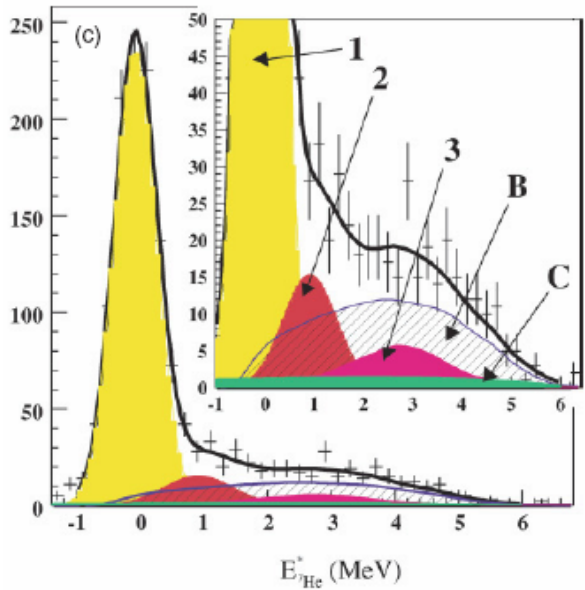
# ${}^7\text{He}$

F. Skaza et al. PR C73 (2006) 044301



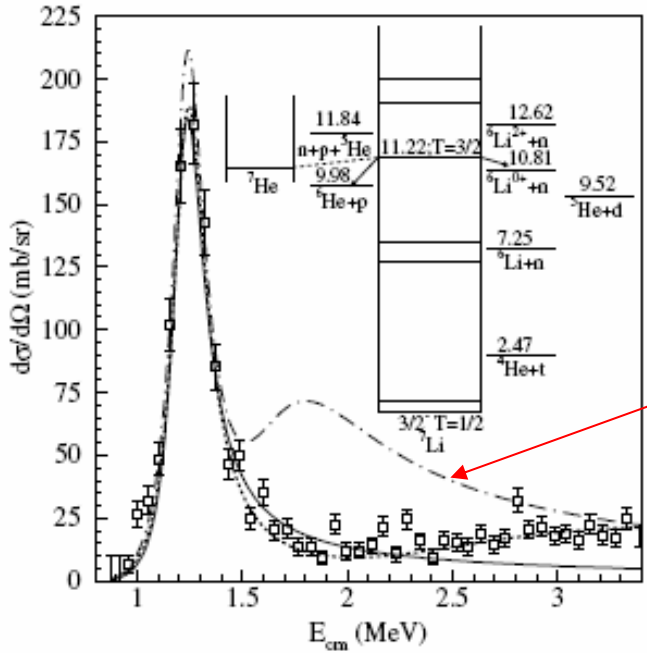
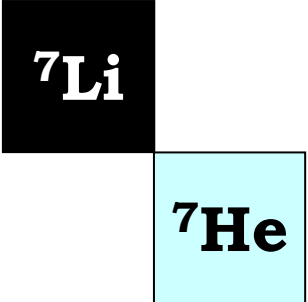
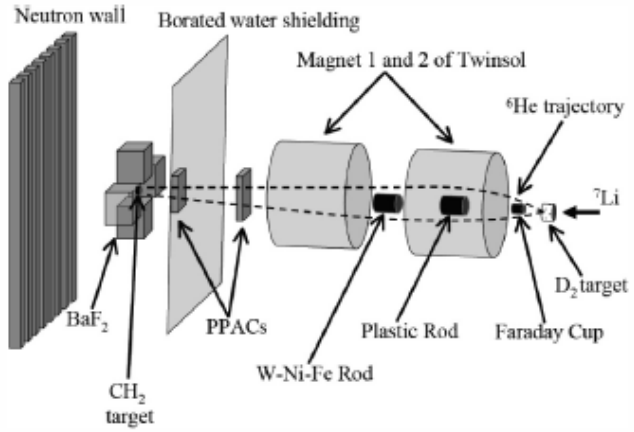
+

$E^* = 0.9(5) \text{ MeV}$   
 $\Gamma = 1.0(9) \text{ MeV}$



SPIRAL  
 ${}^8\text{He}$  @ 15.7 MeV/u

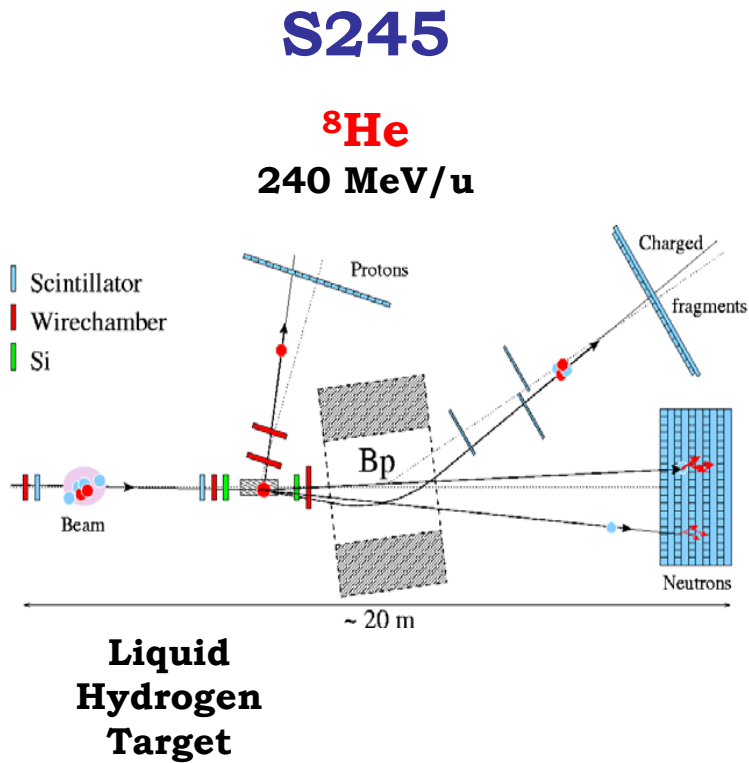
# $^7\text{Li}$



**TwinSol**  
**Notre Dame**  
 **$^6\text{He}$  @ 35 MeV**

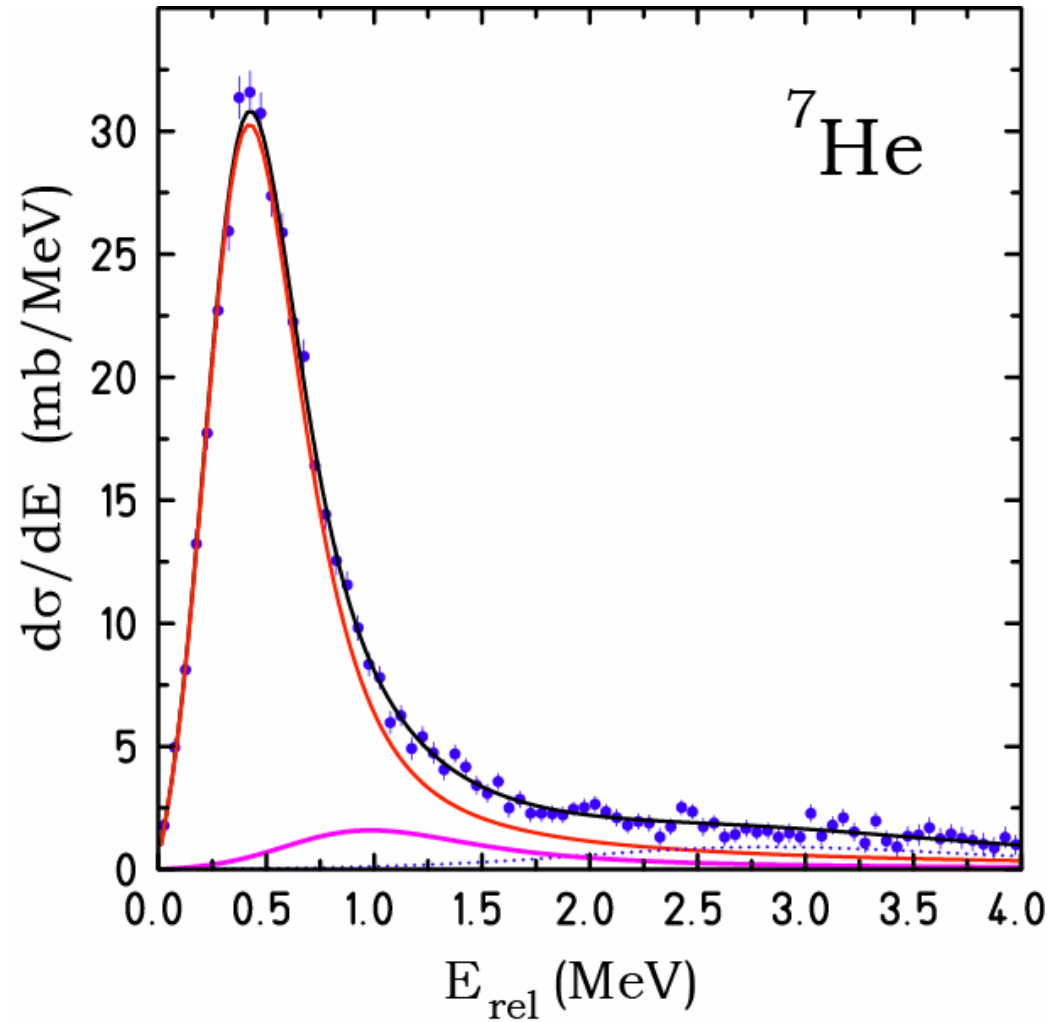
**RCCSM**

D. Halderson. PR C70 (2004) 041603(R)

$$p(^8\text{He}, pn)^7\text{He}$$


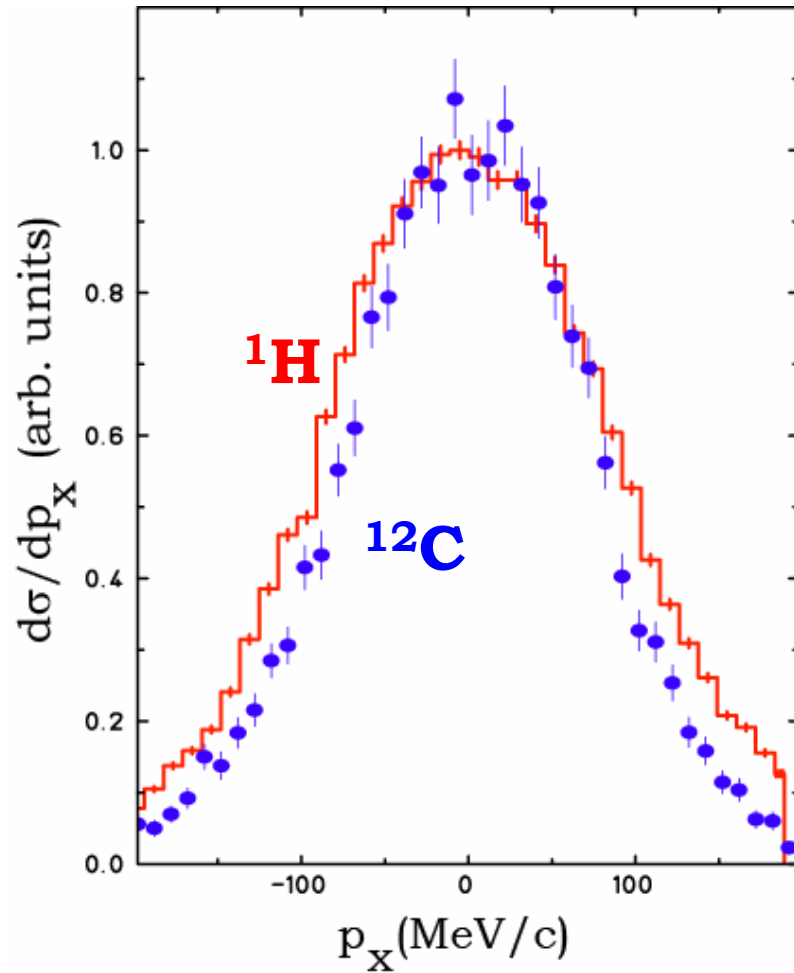
$$E_R = 0.389(2) \text{ MeV}$$

$$\Gamma(E_R) = 0.131(8) \text{ MeV}$$

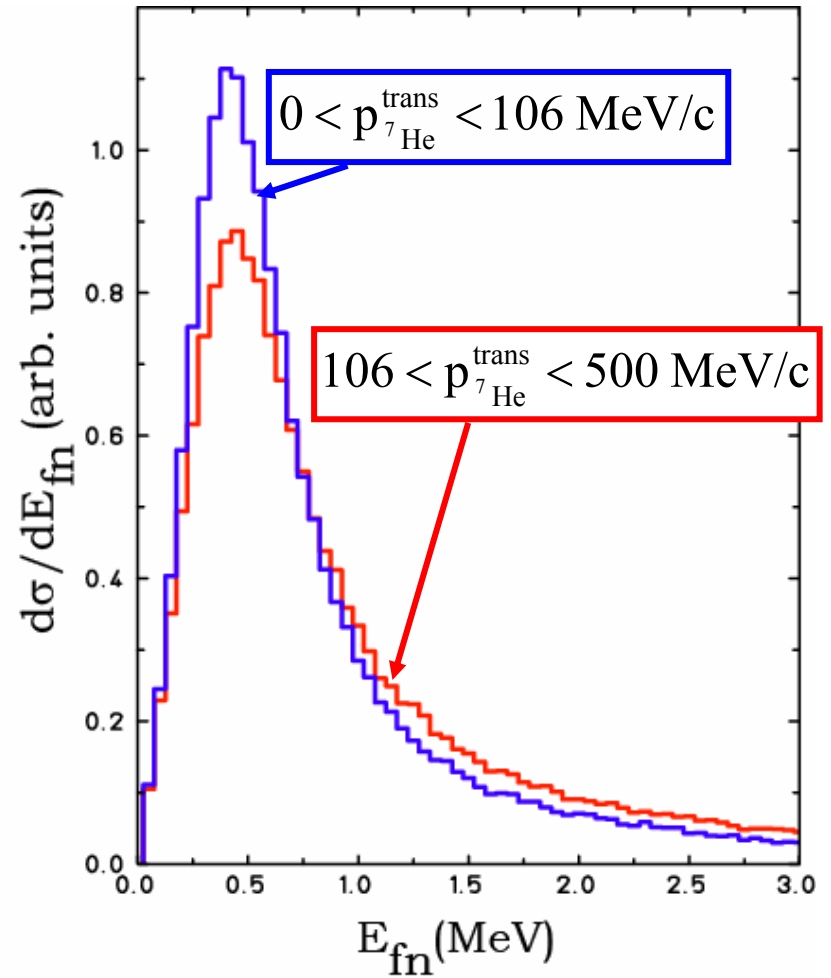


Yu. Aksyutina *et al.* (2008) to be published

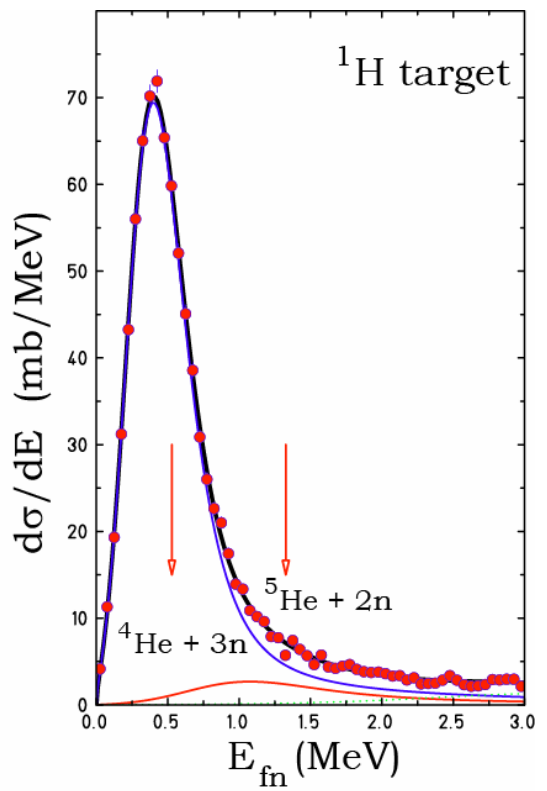
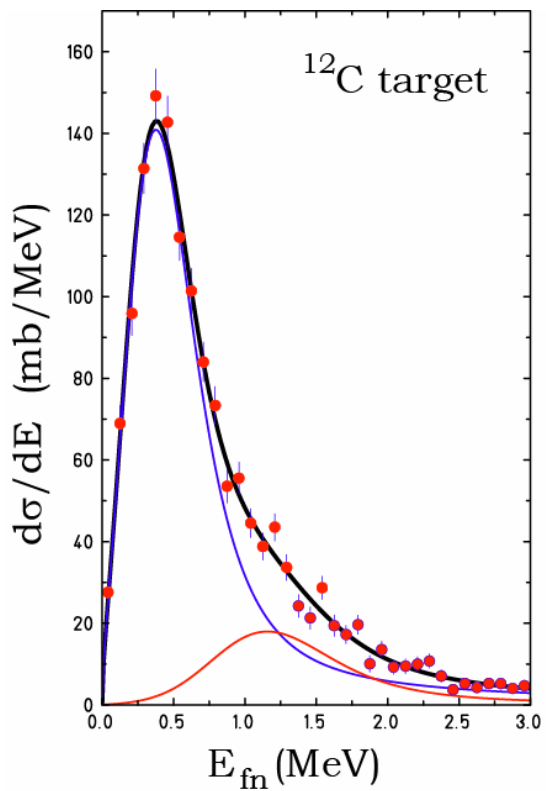
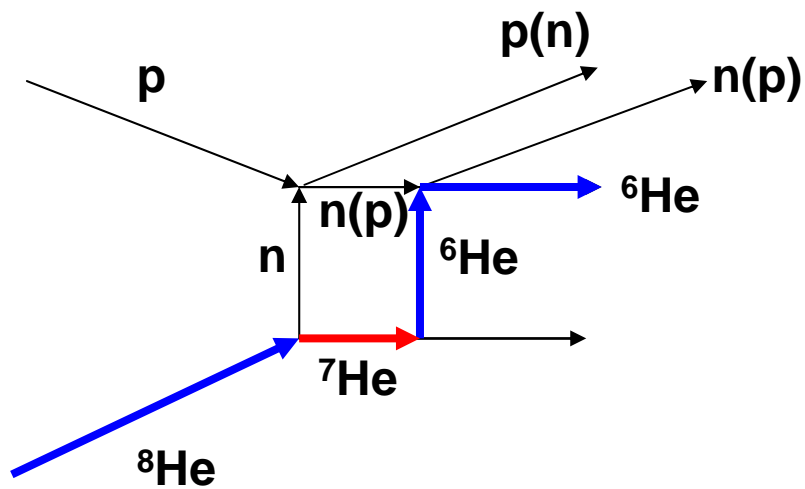
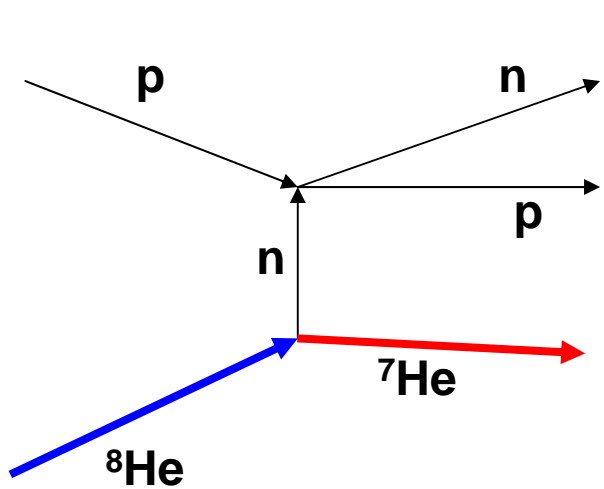
${}^7\text{He}$ , transverse momentum



${}^6\text{He}+n$ , relative energy





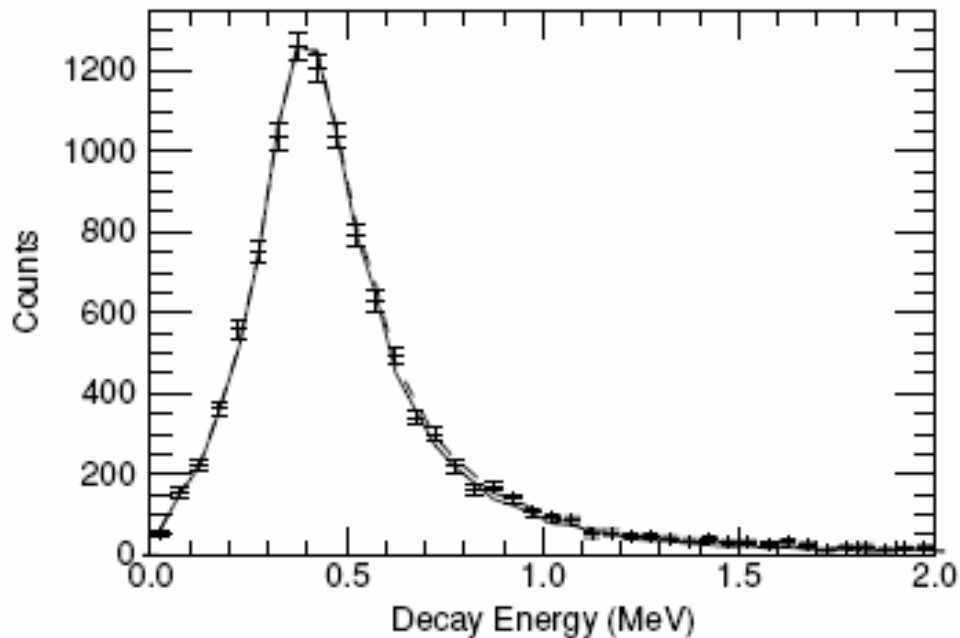


↓  
R. Crespo *et al.*,  
PRC77 (2008) 024601

## Ground state energy and width of ${}^7\text{He}$ from ${}^8\text{Li}$ proton knockout

D. H. Denby,<sup>1</sup> P. A. DeYoung,<sup>1</sup> T. Baumann,<sup>2</sup> D. Bazin,<sup>2</sup> E. Breitbach,<sup>3</sup> J. Brown,<sup>4</sup> N. Frank,<sup>2,5,\*</sup> A. Gade,<sup>2,5</sup> C. C. Hall,<sup>1</sup>  
J. Hinnefeld,<sup>6</sup> C. R. Hoffman,<sup>7</sup> R. Howes,<sup>3</sup> R. A. Jenson,<sup>8</sup> B. Luther,<sup>8</sup> S. M. Mosby,<sup>2,5</sup> C. W. Olson,<sup>8</sup> W. A. Peters,<sup>2,5</sup>  
A. Schiller,<sup>9</sup> A. Spyrou,<sup>2</sup> and M. Thoennessen<sup>2,5</sup>

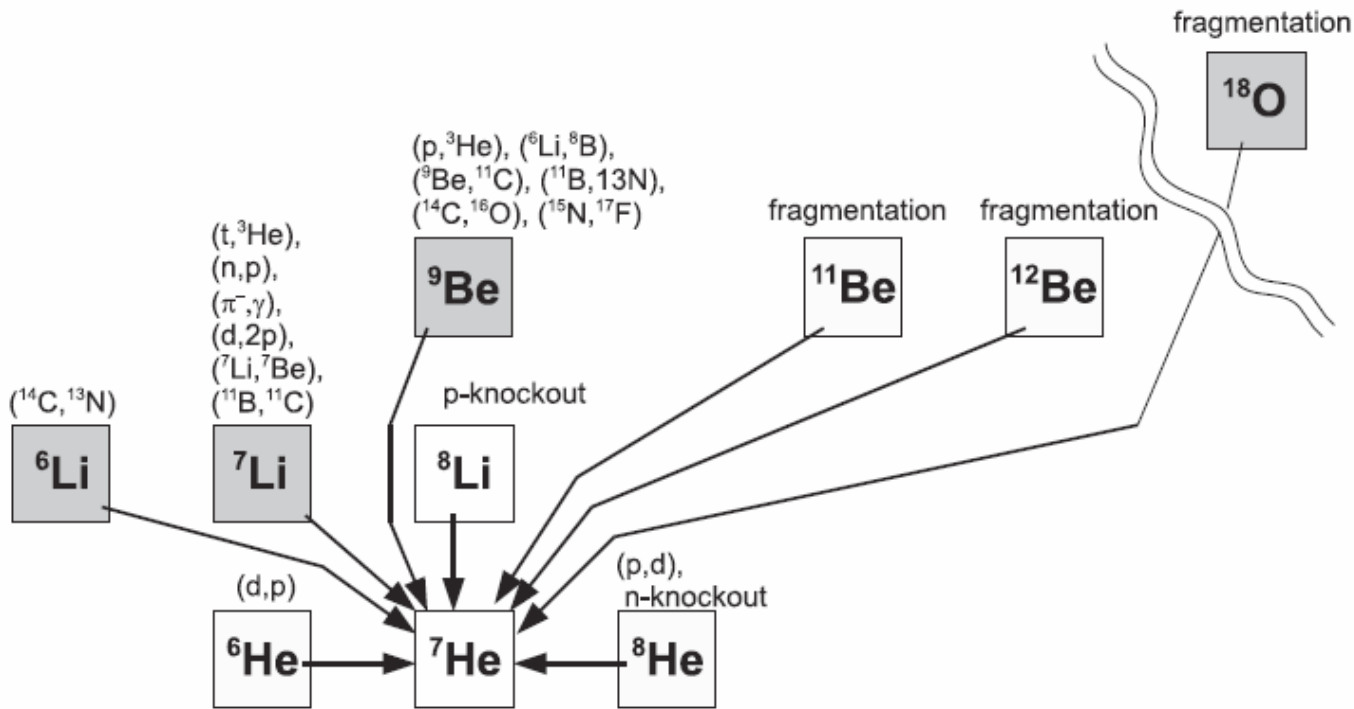
PHYSICAL REVIEW C **78**, 044303 (2008)



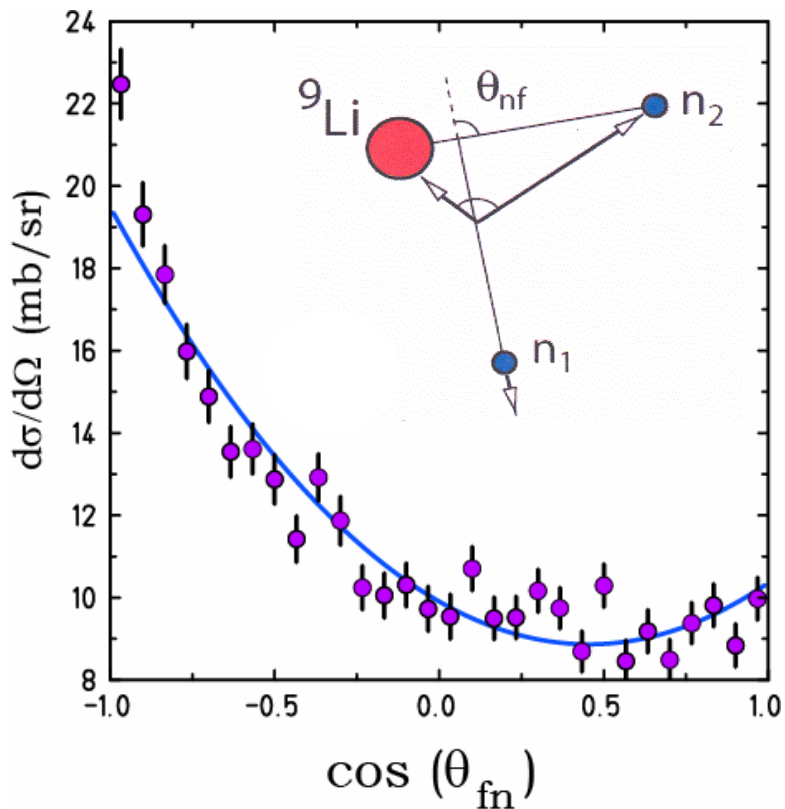
**A1900, MSU**  
 **${}^8\text{Li}$  @ 41 MeV/u**

$E = 400(10) \text{ keV}$   
 $\Gamma = 125_{-15}^{+40} \text{ keV}$

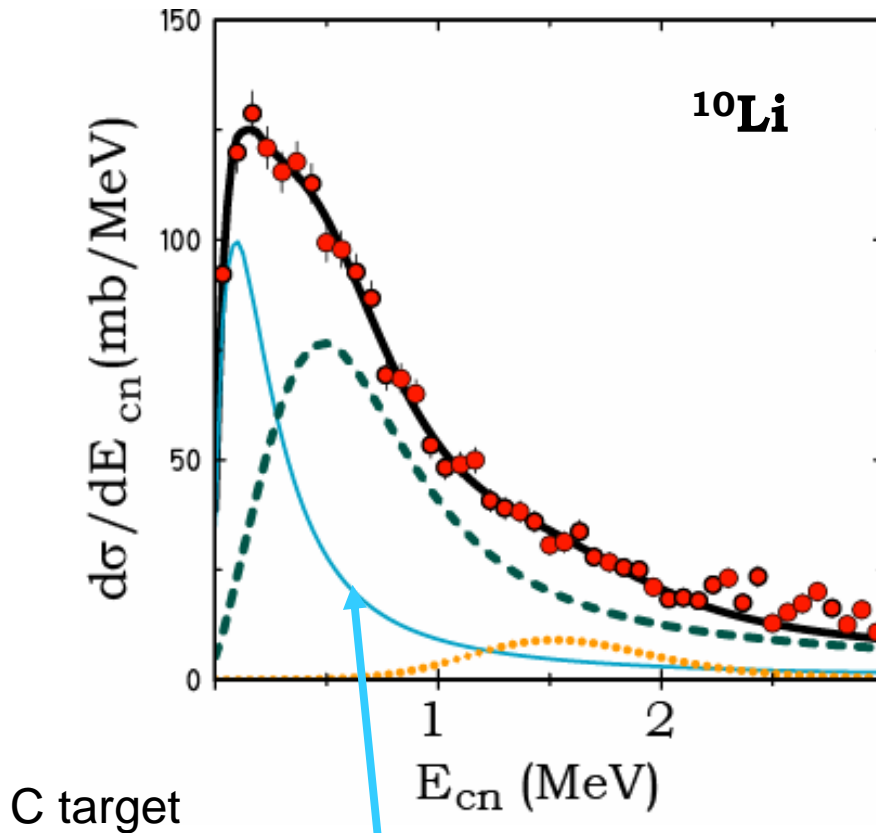
# Reactions resulting in ${}^7\text{He}$



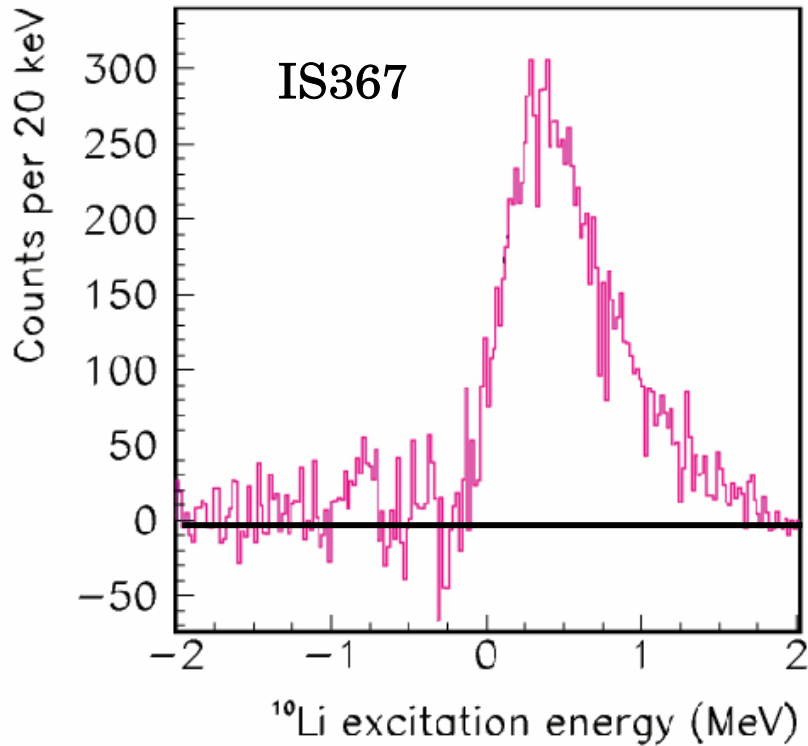
From  
D.H. Denby *et al.*, PR C78 (2008) 044303



$$W(\theta_{fn}) \sim a_0 + \sum_{i=1} a_i \cos^i(\theta_{fn})$$

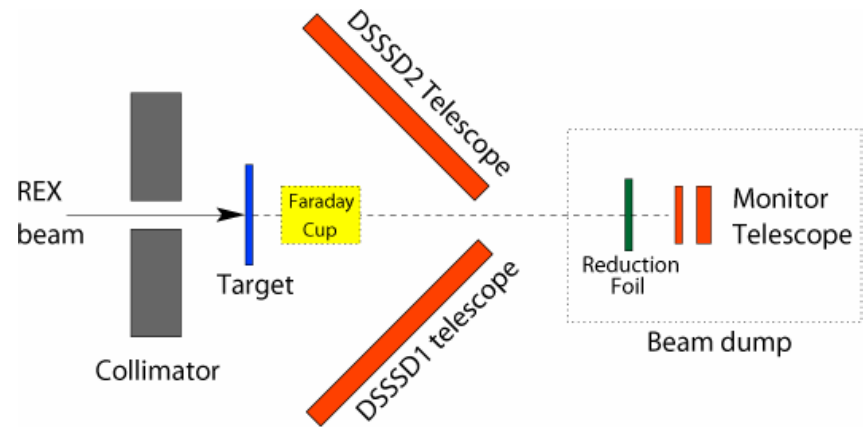


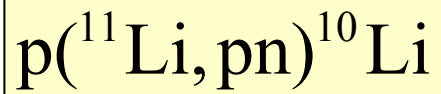
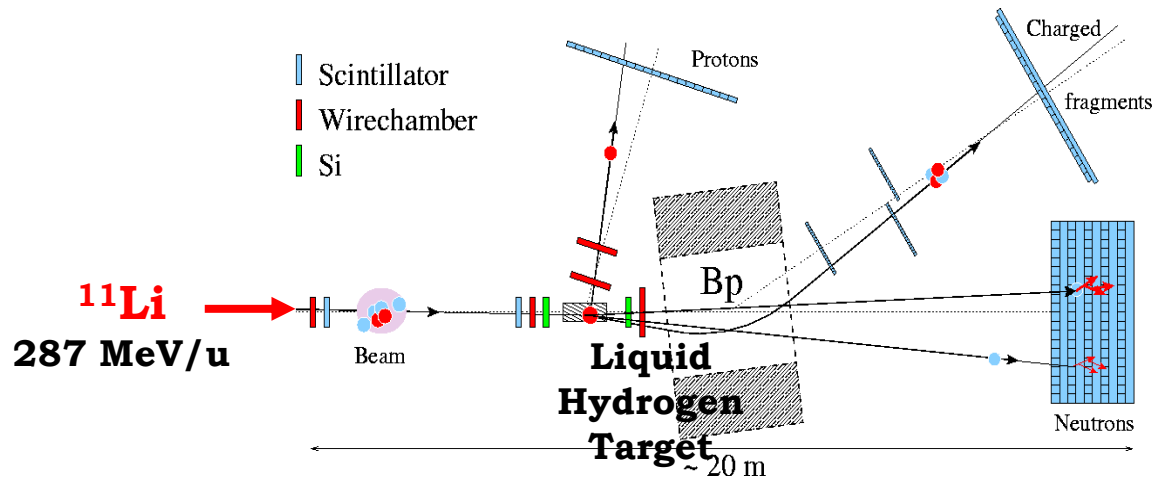
$$a = -30^{+12}_{-31} \text{ fm}$$



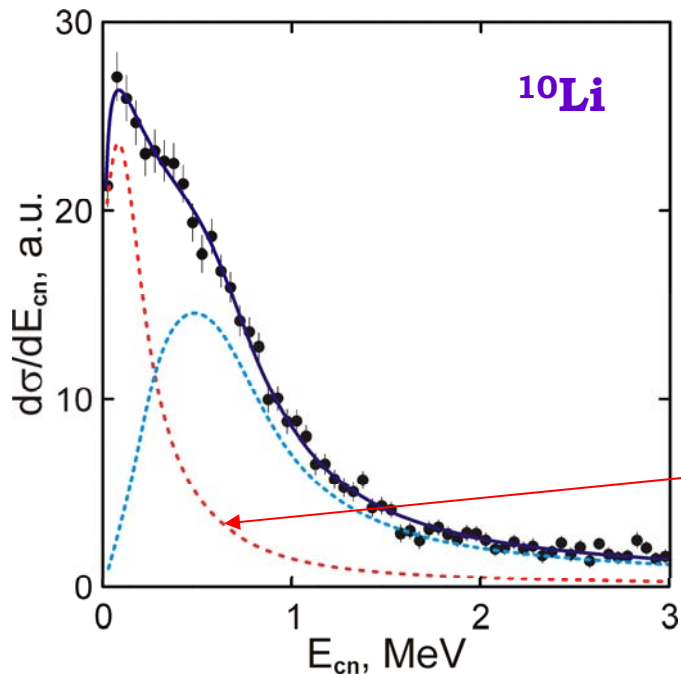
Kirsebom et al., to be published.

**2.77 MeV/u**





**FRS-ALADIN-LAND@GSI**



$$\frac{d\sigma}{dE_{fn}} \propto p_{fn} \left[ \frac{1}{k^2 + p_{fn}^2} \right]^2 \left[ \cos(\delta) + \frac{k}{p_{fn}} \sin(\delta) \right]^2$$

$$p_{fn} \cot(\delta) = -\frac{1}{a} + \frac{1}{2} r_0 p_{fn}^2 + O(p_{fn}^4)$$

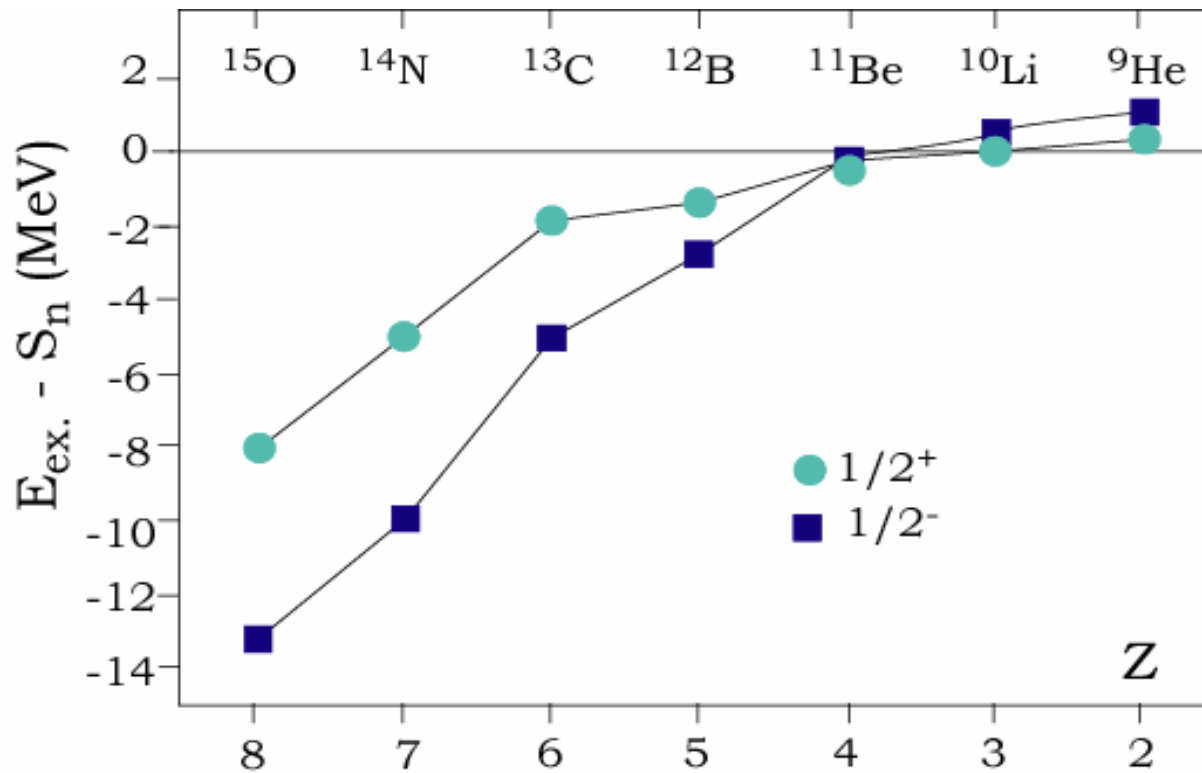
Yu. Aksyutina., PL B666 (2008) 430

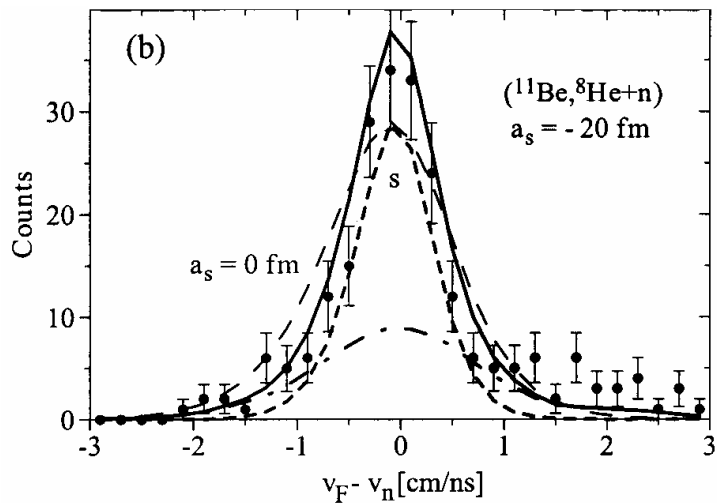
$$k = \sqrt{2\mu\varepsilon}$$

$$\varepsilon = 352(22) \text{ keV}$$

$$a = -22.4(4.8) \text{ fm}$$

# The N=7 Isotones

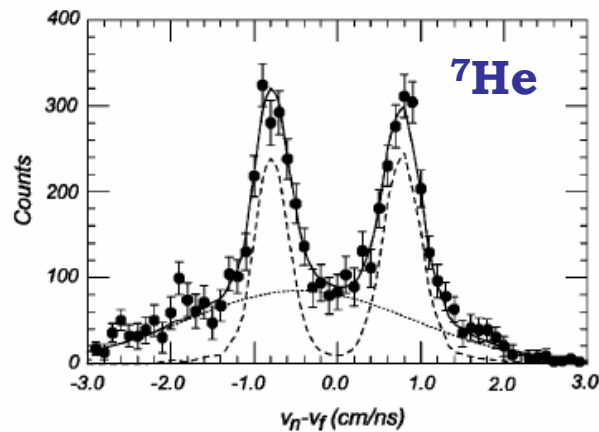
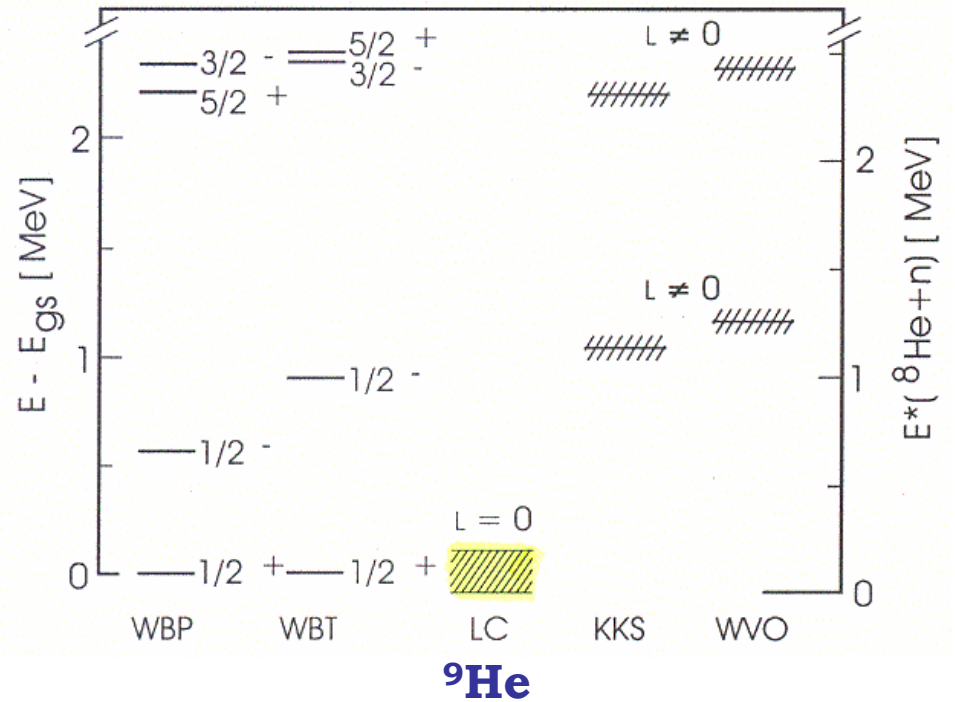




L. Chen *et al.* PL B 505 (2001) 21

**28 MeV/u  $^{11}\text{Be}$**

**$(^{11}\text{Be}, ^8\text{He}+n)$**

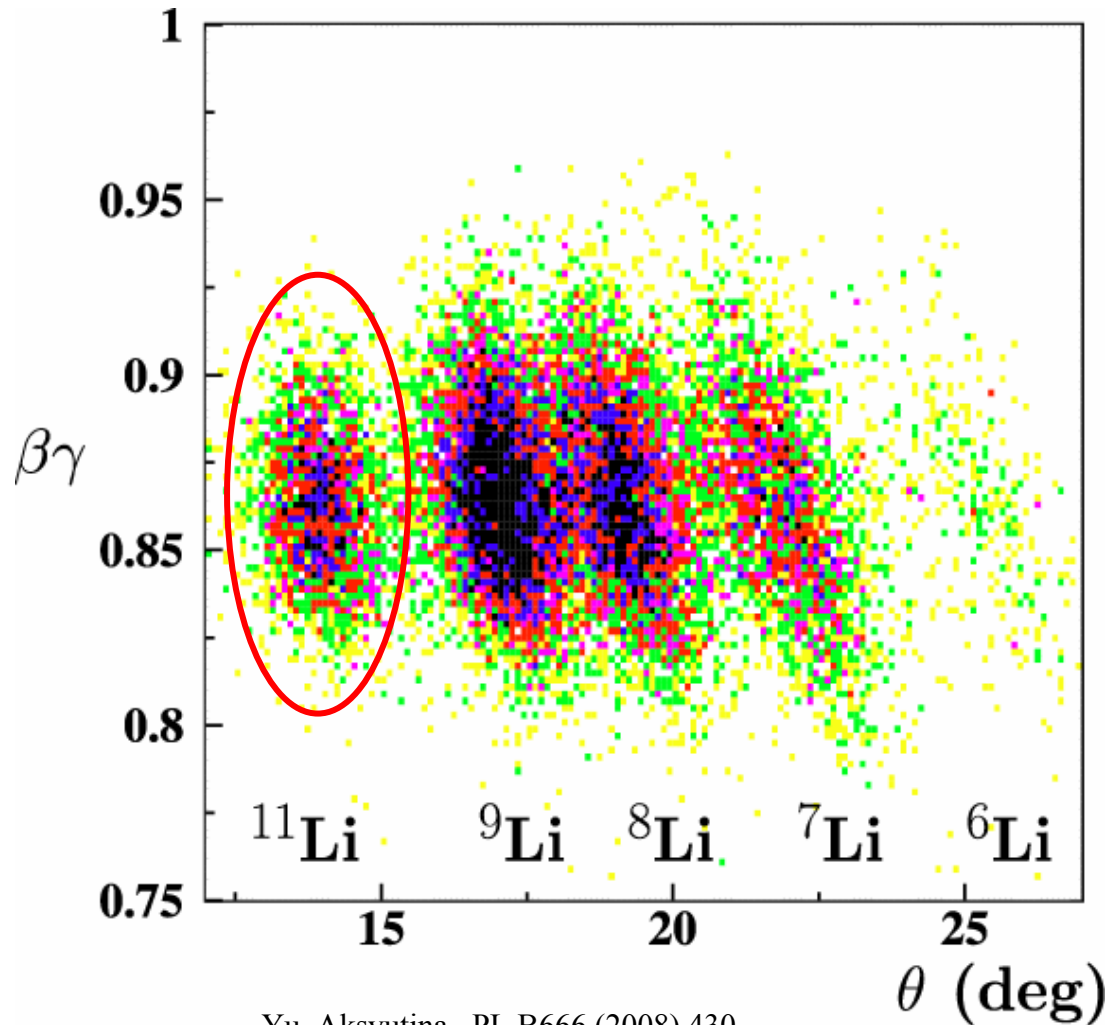


M. Thoennessen *et al.* PR C 59 (1999) 111

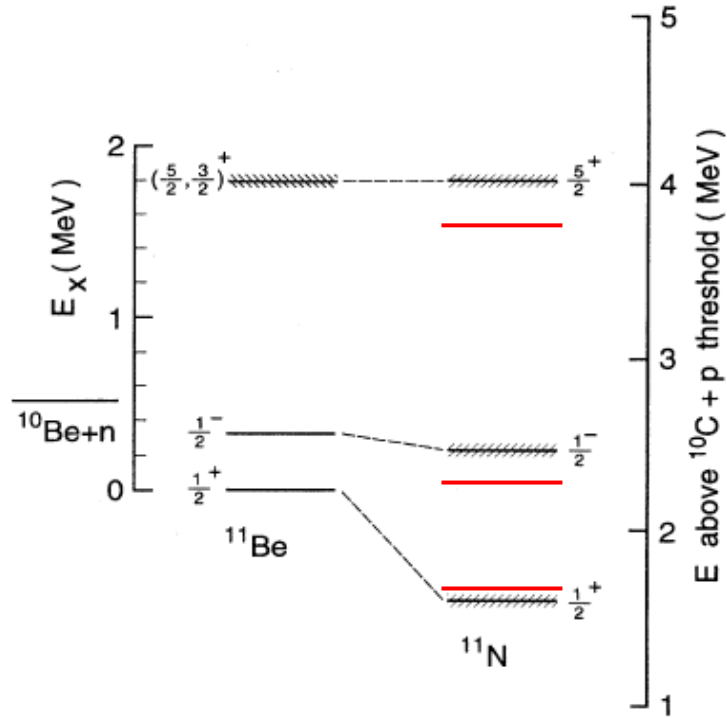


# Exotic Beams

$^{14}\text{Be}$  @ 310 MeV/u

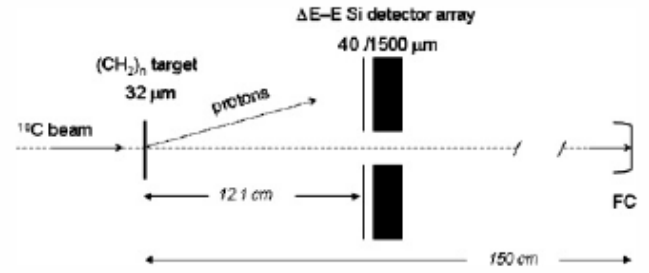


Yu. Aksyutina., PL B666 (2008) 430

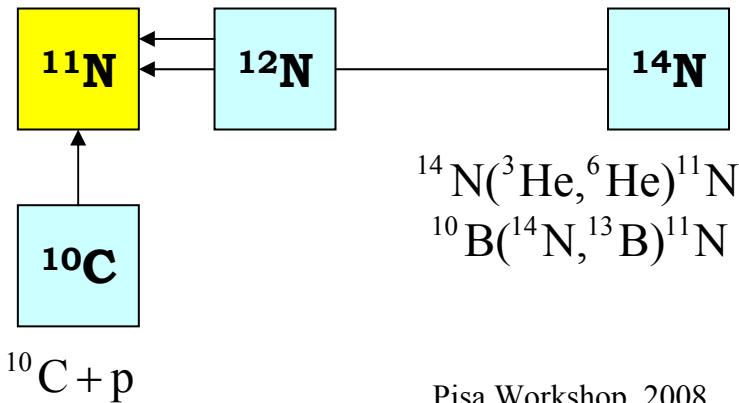
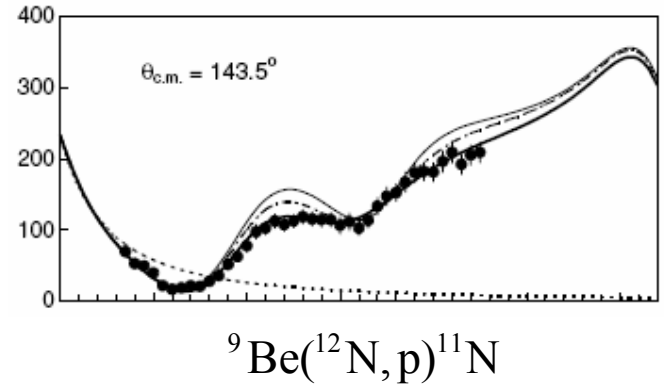


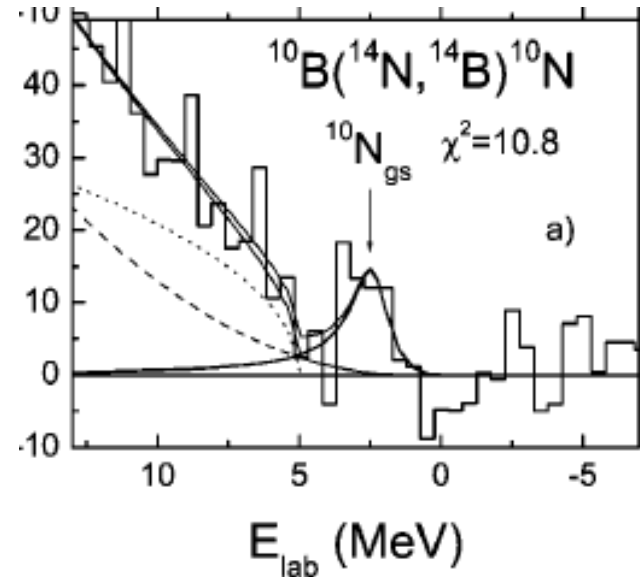
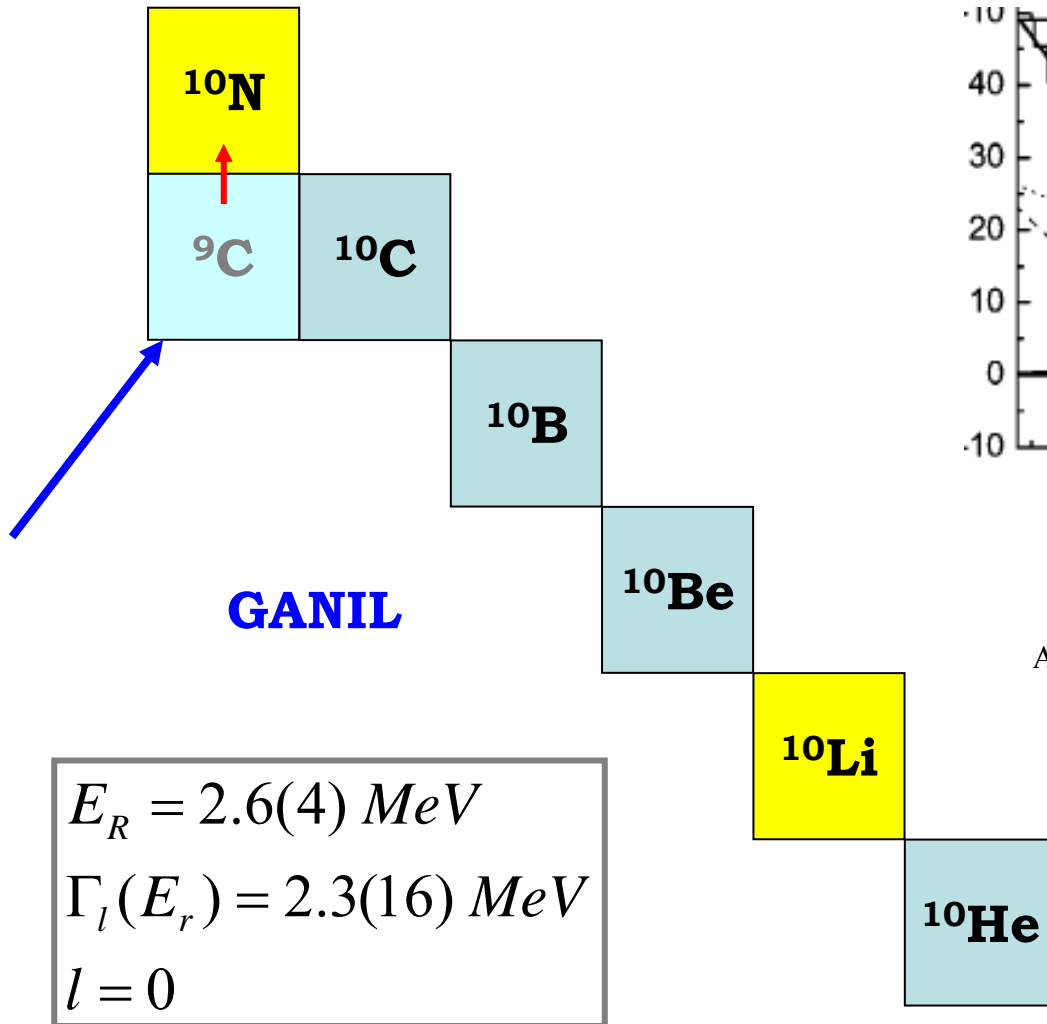
H.T. Fortune *et al.* PR C51(1995) 3023

**CYCLONE**  
**<sup>9</sup>C @ 25.5 MeV**



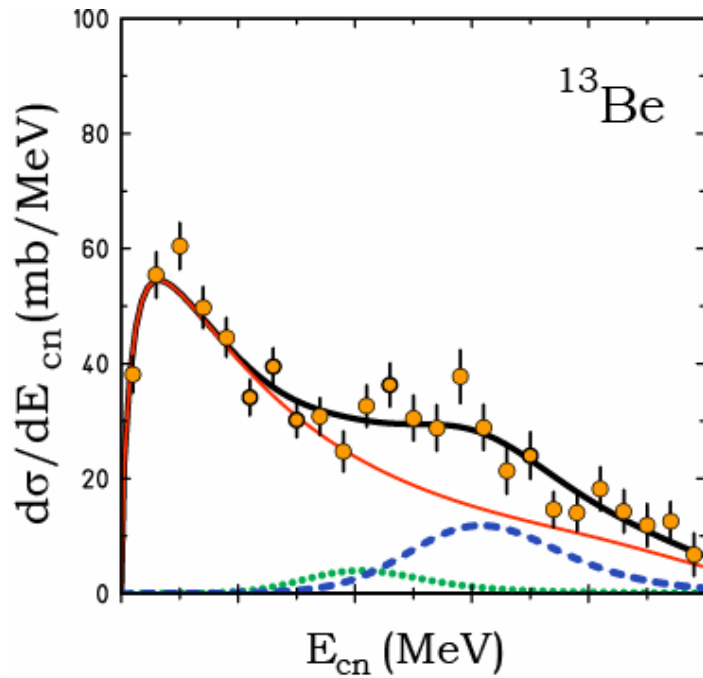
E. Casarejos *et al.* PR C73(2006) 014319



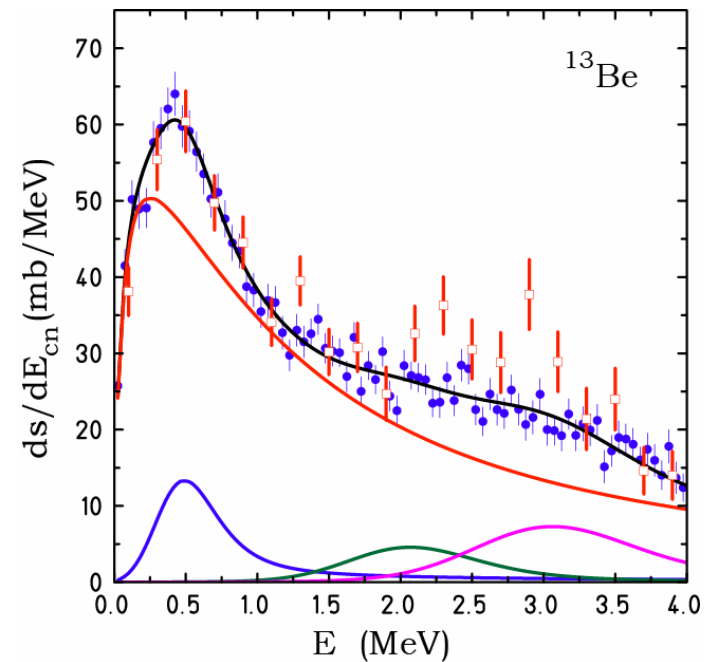


A. Lépine-Szily *et al.* PR C65(2002) 054318

${}^7\text{Be}$	${}^8\text{Be}$ unbound	${}^9\text{Be}$	${}^{10}\text{Be}$ $1.6 \cdot 10^6 \text{ y}$	${}^{11}\text{Be}$ 13.8 s	${}^{12}\text{Be}$ 23.6 ms	${}^{13}\text{Be}$ unbound	${}^{14}\text{Be}$ 4.35 ms
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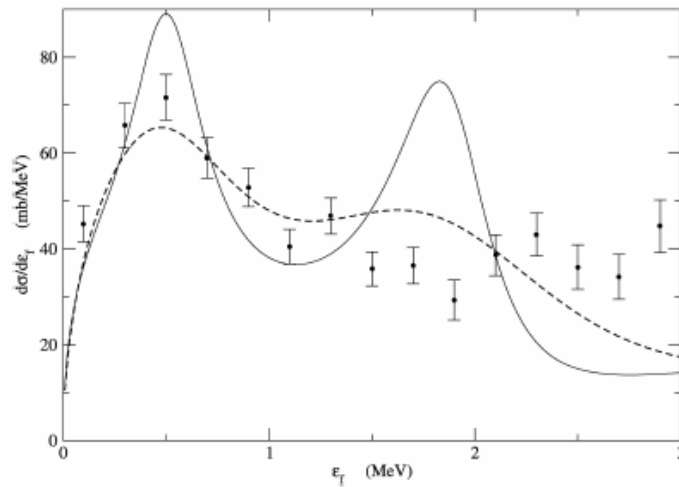
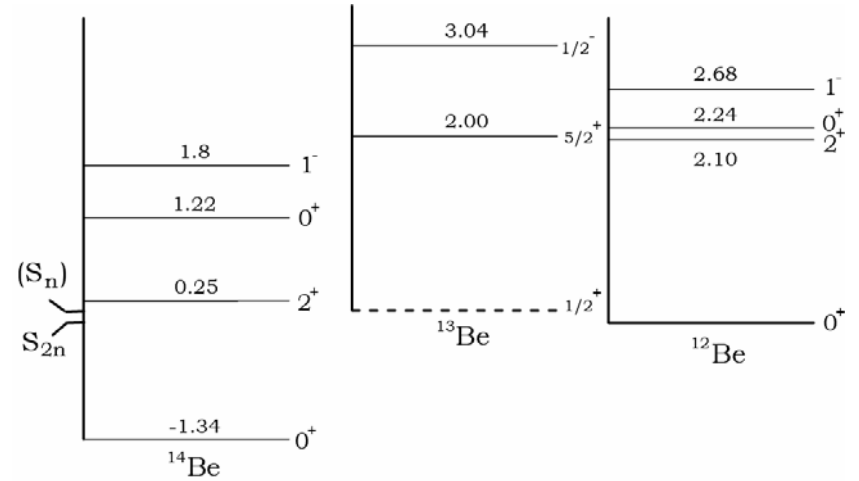
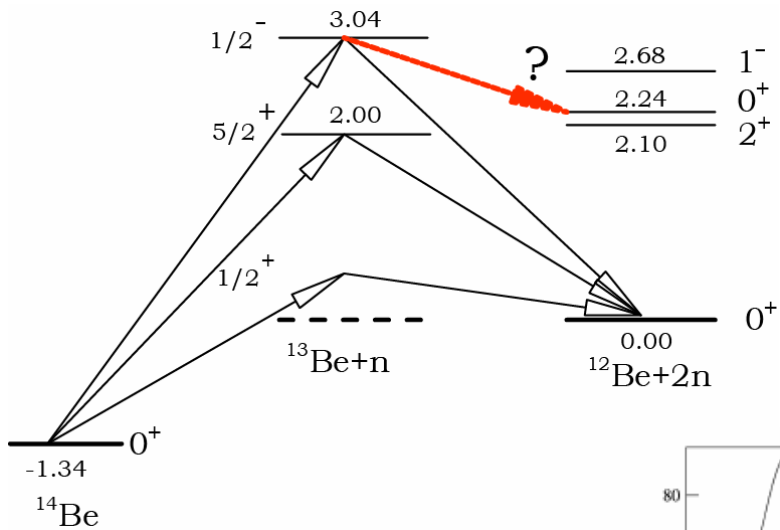


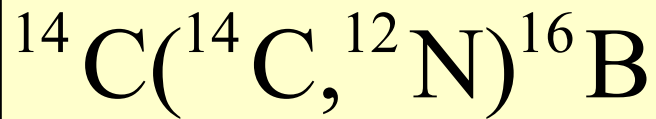
H. Simon *et al.*, NP A791 (2007) 267



Yu. Aksyutina *et al.* To be publised

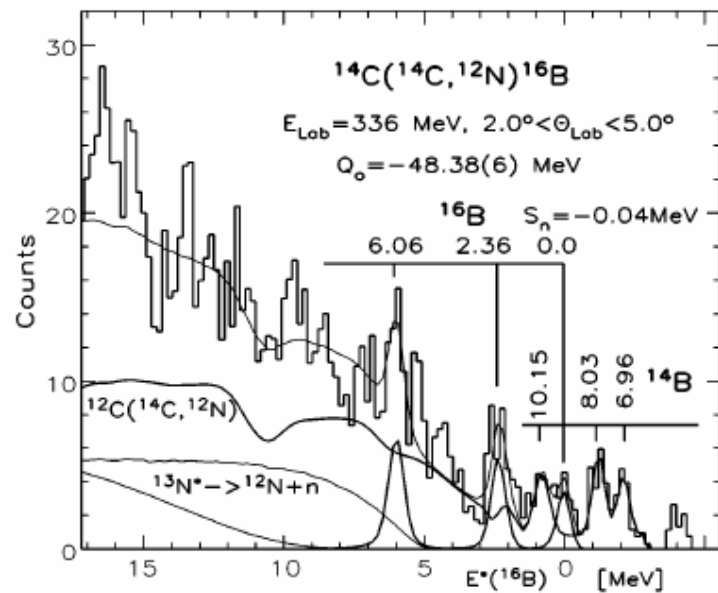
# Population of excited states in $^{12}\text{Be}$ ?





<b><math>^{14}\text{C}</math></b> 5730 a		<b><math>^{17}\text{C}</math></b> 193 ms	<b><math>^{18}\text{C}</math></b> 62 ms
	<b><math>^{14}\text{B}</math></b> 82 ms	<b><math>^{15}\text{B}</math></b> 10.4 ms	<b><math>^{16}\text{B}</math></b> unbound
	<b><math>^{14}\text{Be}</math></b> 4.35 ms		

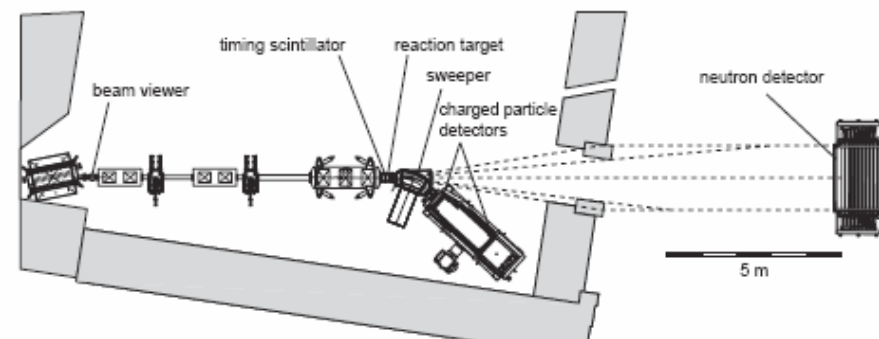
HMI Berlin  
 $^{14}\text{C}$  @ 336 MeV



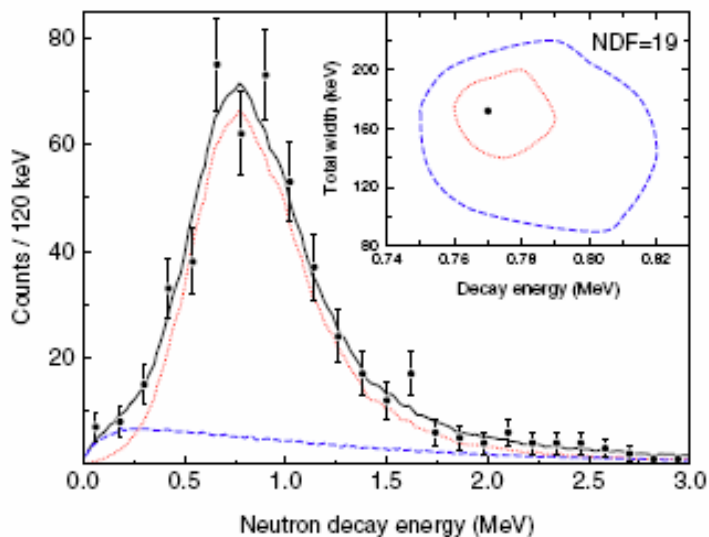
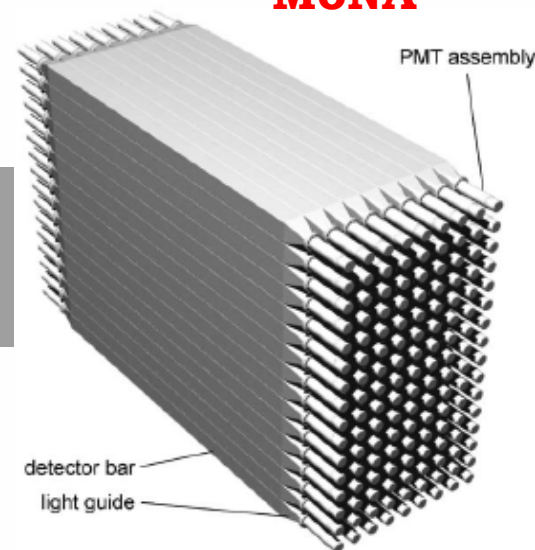
R. Kalpakchieva ., EP J A7 (2000) 451

<b><math>^{24}\text{F}</math></b> 0.34 s	<b><math>^{25}\text{F}</math></b> 50 ms	<b><math>^{26}\text{F}</math></b> 10.2 ms ↓	<b><math>^{27}\text{F}</math></b> 4.9 ms	<b><math>^{28}\text{F}</math></b> unbound	<b><math>^{29}\text{F}</math></b> 2.6 ms
<b><math>^{23}\text{O}</math></b> 82 ms	<b><math>^{24}\text{O}</math></b> 61 ms	<b><math>^{25}\text{O}</math></b> unbound			

**MSU**



**MoNA**



$$E_{\text{decay}} = 770_{-10}^{+20} \text{ keV}$$

$$\Gamma = 172(30) \text{ keV}$$

C.R. Hoffman *et al.* PRL 100(2008) 152502

T. Baumann *et al.* NIM A543(2005) 517

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# HIE-ISOLDE

