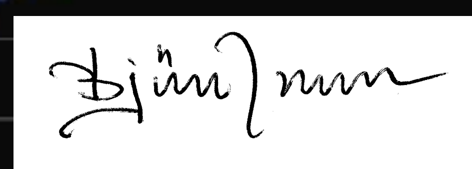
ISOLDE Nuclear Reaction
and
Nuclear Structure Course
22-25 April 2014

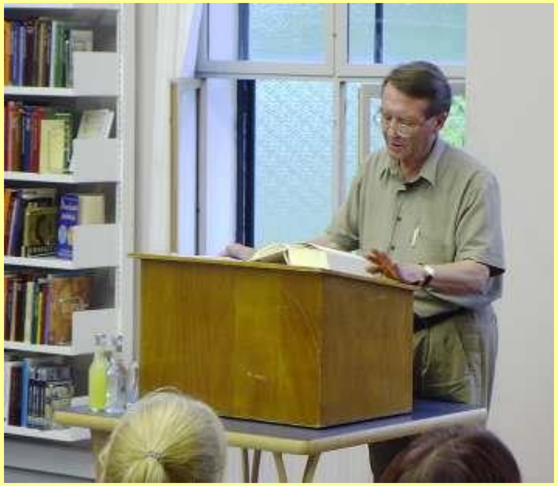
Nuclear Reaction at Intermediate to Relativistic Energies: what data tell us (I)



I do not know much about anything;
what I know is already commonplace.
Wouldn't it be nice to know just one fact,
for example the proportions of the spots of the ladybird.

Jeg kender ikke meget til meget;
det jeg kender til er i forvejen meget udbredt.
Tænk at vide bare een bestemt ting,
for eksempel forholdet mellem mariehønens pletter.

Benny Andersen,
Viden 1965

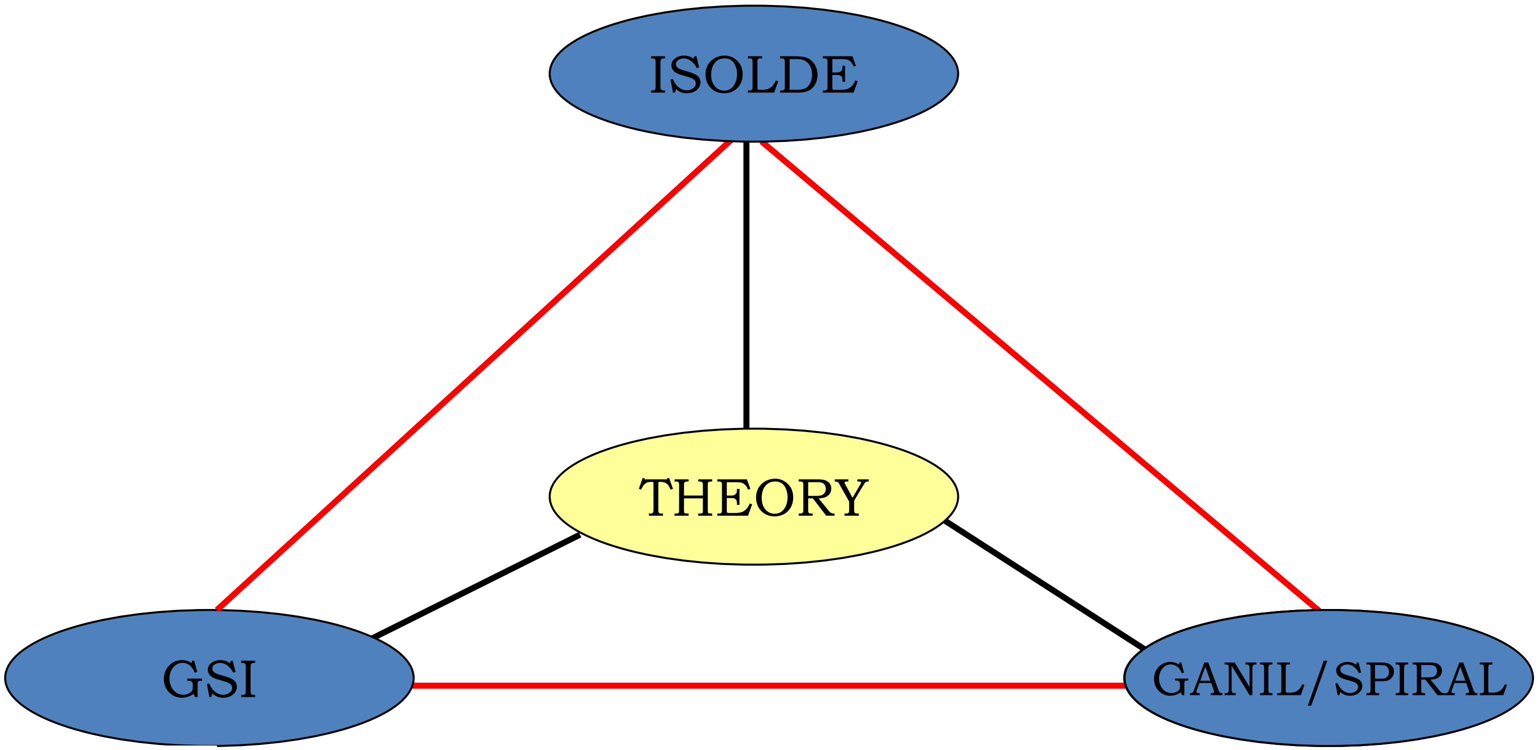


Physics With Radioactive Beams

Nobel Symposium NS 152

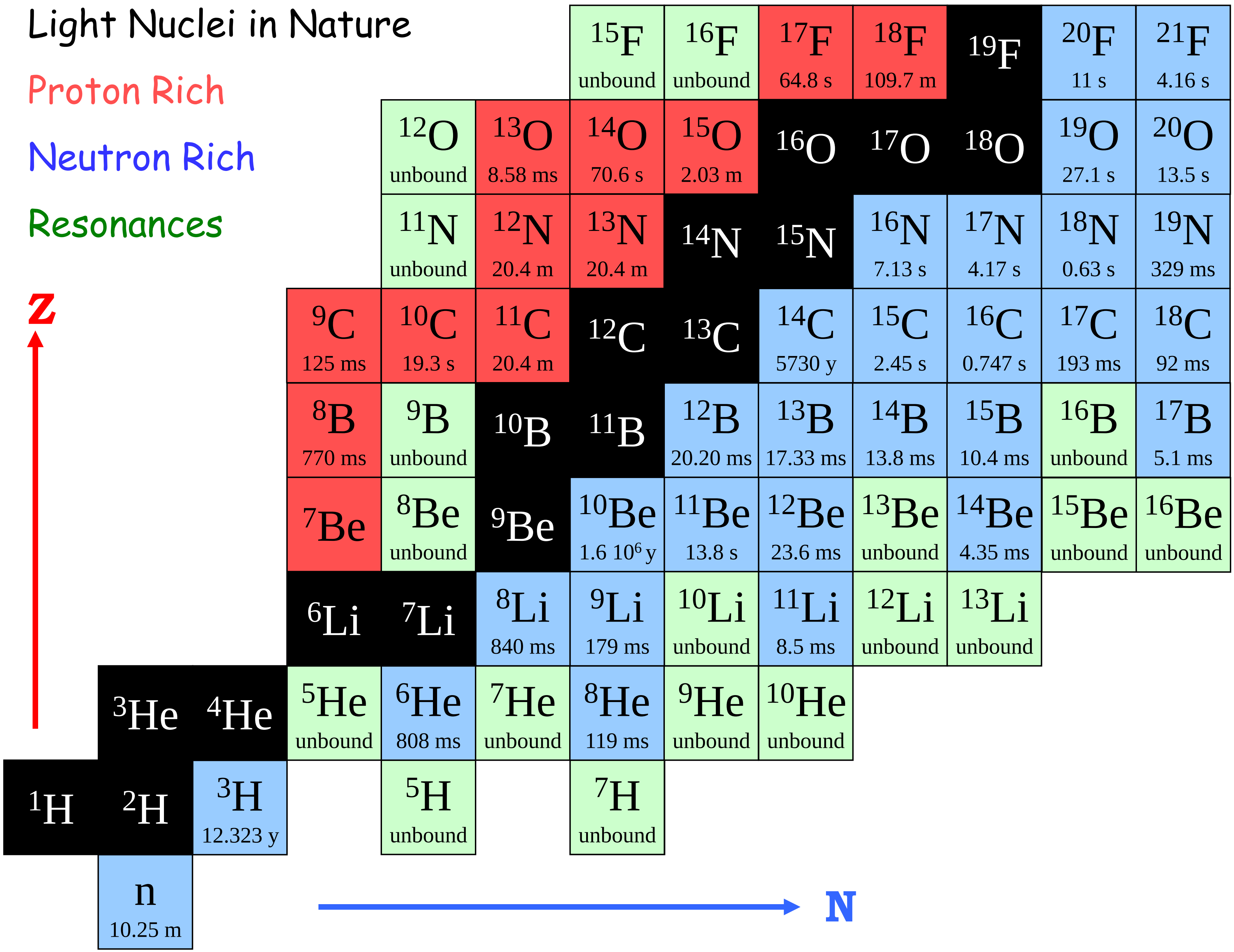
HIE-ISOLDE

REX-ISOLDE

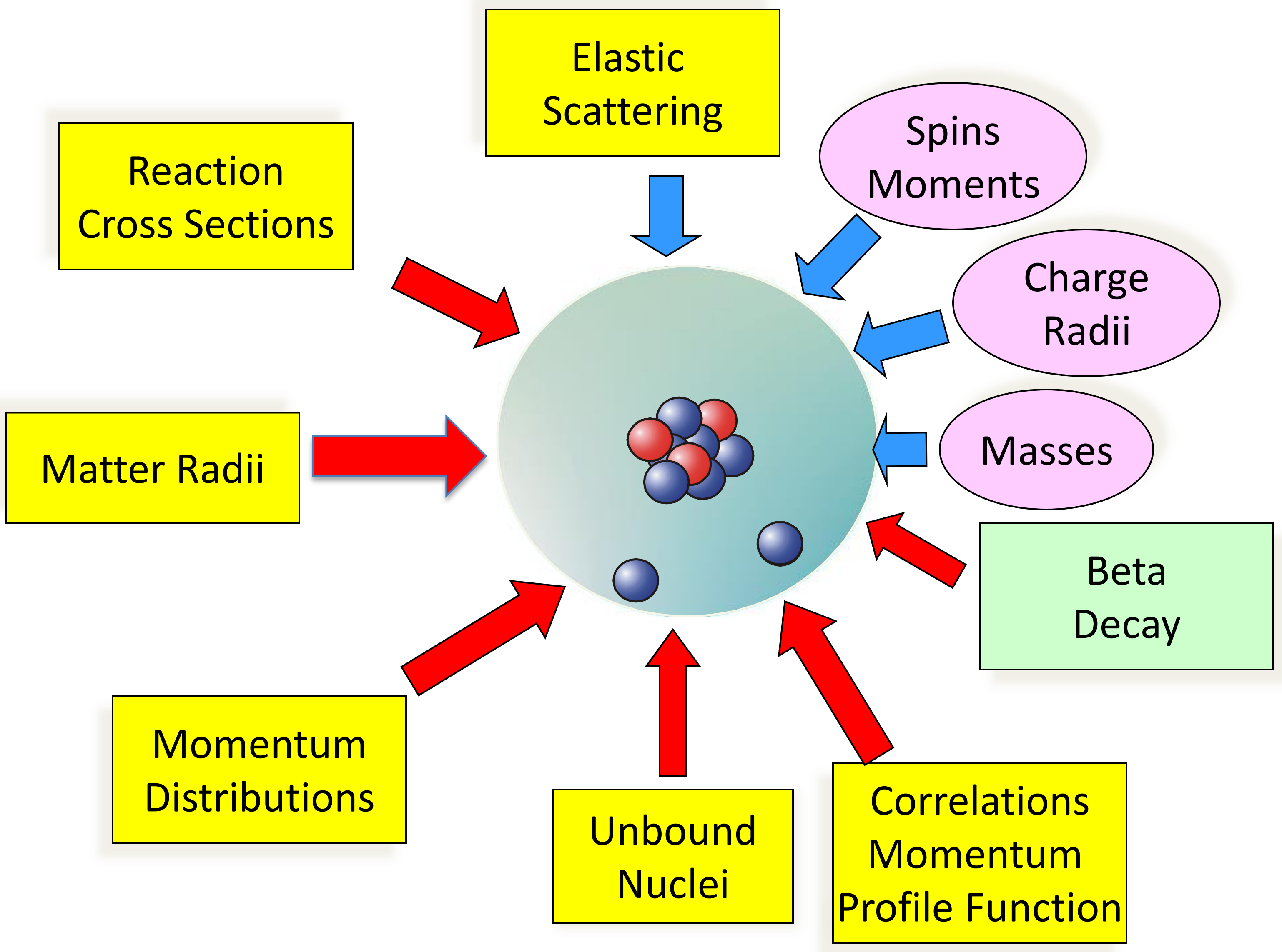


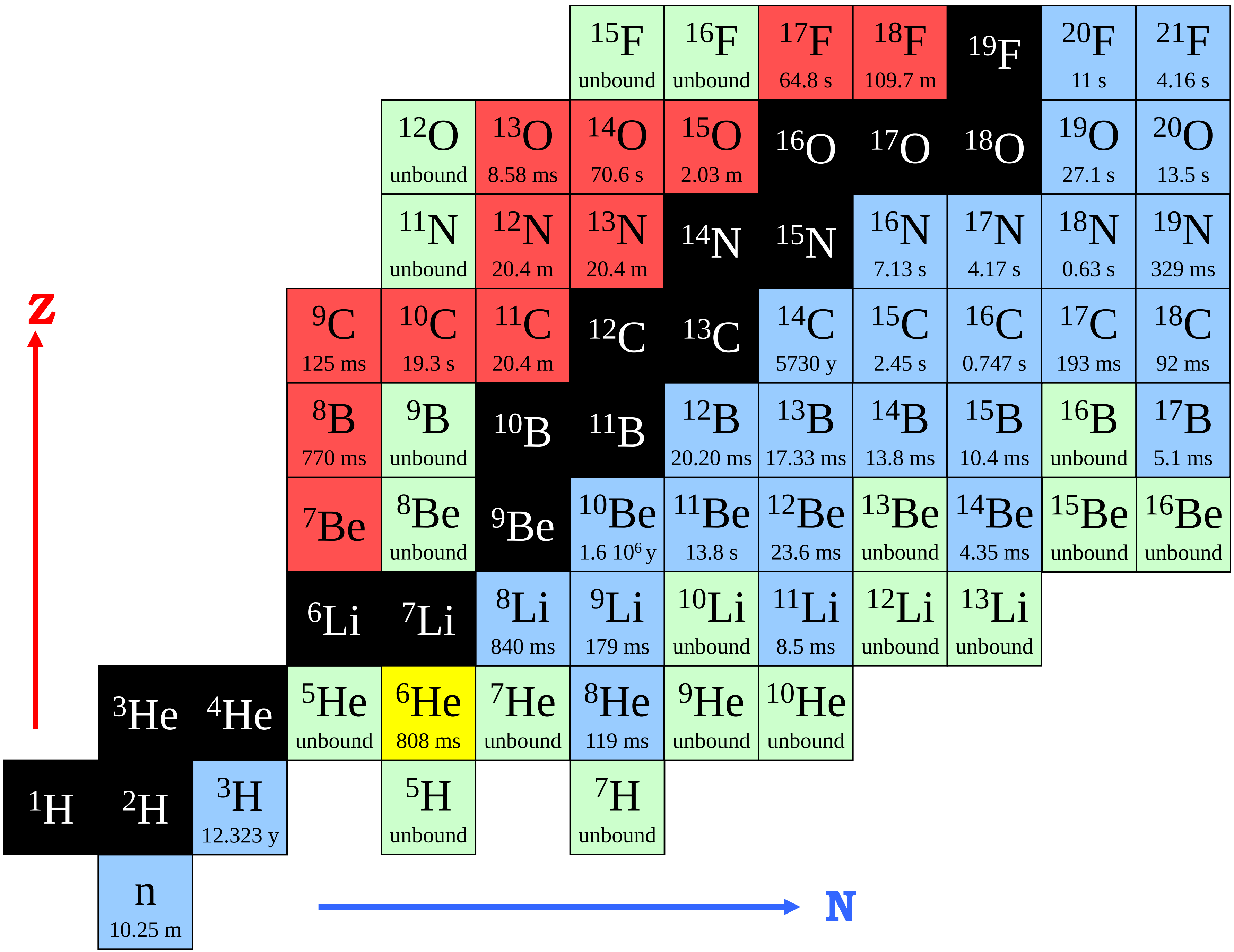
FAIR

Spiral2


Light Nuclei in Nature
Proton Rich
Neutron Rich
Resonances
Z
N
^{15}F unbound
^{16}F unbound
^{17}F 64.8 s
^{18}F 109.7 m
^{19}F
^{20}F 11 s
^{21}F 4.16 s
^{12}O unbound
^{13}O 8.58 ms
^{14}O 70.6 s
^{15}O 2.03 m
^{16}O
^{17}O
^{18}O
^{19}O 27.1 s
^{20}O 13.5 s
^{11}N unbound
^{12}N 20.4 m
^{13}N 20.4 m
^{14}N
^{15}N
^{16}N 7.13 s
^{17}N 4.17 s
^{18}N 0.63 s
^{19}N 329 ms
^{9}C 125 ms
^{10}C 19.3 s
^{11}C 20.4 m
^{12}C
^{13}C
^{14}C 5730 y
^{15}C 2.45 s
^{16}C 0.747 s
^{17}C 193 ms
^{18}C 92 ms
^{8}B 770 ms
^{9}B unbound
^{10}B
^{11}B
^{12}B 20.20 ms
^{13}B 17.33 ms
^{14}B 13.8 ms
^{15}B 10.4 ms
^{16}B unbound
^{17}B 5.1 ms
^{7}Be
^{8}Be unbound
^{9}Be
^{10}Be 1.6 10^{6} y
^{11}Be 13.8 s
^{12}Be 23.6 ms
^{13}Be unbound
^{14}Be 4.35 ms
^{15}Be unbound
^{16}Be unbound
^{6}Li
^{7}Li
^{8}Li 840 ms
^{9}Li 179 ms
^{10}Li unbound
^{11}Li 8.5 ms
^{12}Li unbound
^{13}Li unbound
^{3}He
^{4}He
^{5}He unbound
^{6}He 808 ms
^{7}He unbound
^{8}He 119 ms
^{9}He unbound
^{10}He unbound
^{1}H
^{2}H
^{3}H 12.323 y
^{5}H unbound
^{7}H unbound
n 10.25 m

Experimental Studies of Dripline Nuclei





^{15}F unbound
^{16}F unbound
^{17}F 64.8 s
^{18}F 109.7 m
^{19}F
^{20}F 11 s
^{21}F 4.16 s
^{12}O unbound
^{13}O 8.58 ms
^{14}O 70.6 s
^{15}O 2.03 m
^{16}O
^{17}O
^{18}O
^{19}O 27.1 s
^{20}O 13.5 s
^{11}N unbound
^{12}N 20.4 m
^{13}N 20.4 m
^{14}N
^{15}N
^{16}N 7.13 s
^{17}N 4.17 s
^{18}N 0.63 s
^{19}N 329 ms
Z
^{9}C 125 ms
^{10}C 19.3 s
^{11}C 20.4 m
^{12}C
^{13}C
^{14}C 5730 y
^{15}C 2.45 s
^{16}C 0.747 s
^{17}C 193 ms
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^{8}B 770 ms
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^{11}B
^{12}B 20.20 ms
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^{15}B 10.4 ms
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^{17}B 5.1 ms
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^{8}Be unbound
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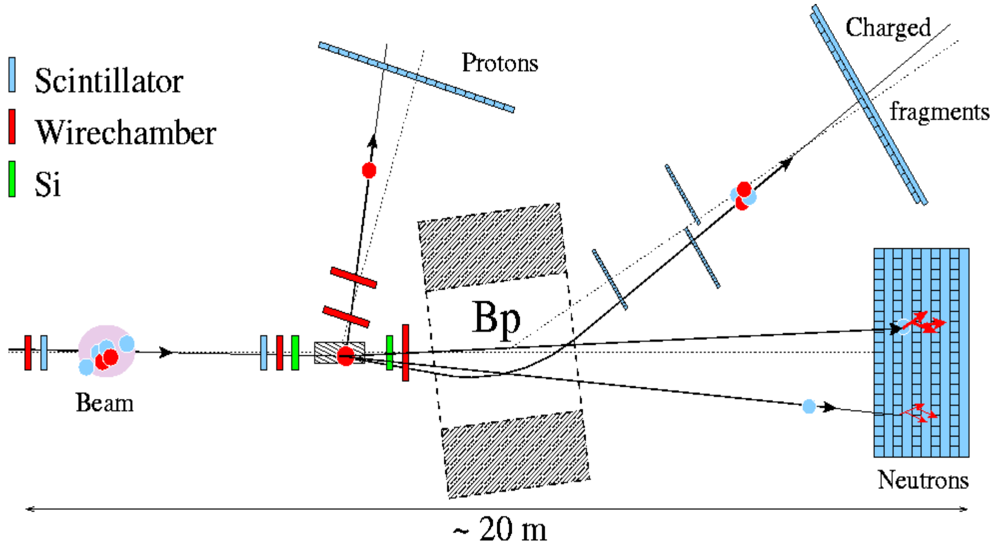
^{9}He unbound
^{10}He unbound
^{1}H
^{2}H
^{3}H 12.323 y
^{5}H unbound
^{7}H unbound
n 10.25 m
N

^{6}He



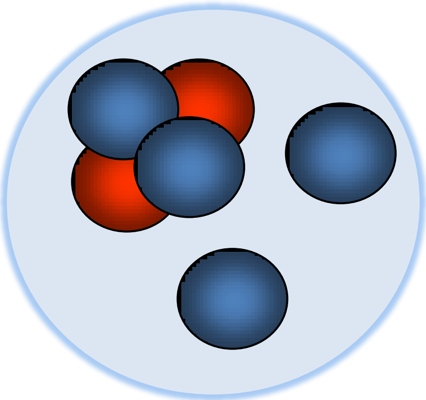
$$\mathbf{p}_{n\alpha} = \frac{m_n m_\alpha}{m_n + m_\alpha} \left[\frac{\mathbf{p}_{n_2}}{m_n} - \frac{\mathbf{p}_\alpha}{m_\alpha} \right]$$

$$\mathbf{p}_{n(n\alpha)} = \frac{m_n(m_\alpha + m_n)}{2m_n + m_\alpha} \left[\frac{\mathbf{p}_{n_1}}{m_n} - \frac{(\mathbf{p}_{n_2} + \mathbf{p}_\alpha)}{m_n + m_\alpha} \right]$$

$$\mathbf{p}_{cm} = \mathbf{p}_{n_1} + \mathbf{p}_{n_2} + \mathbf{p}_\alpha \qquad (\mathbf{p}_{cm} = 0)\ \mathbf{p}_{n_1} = -\left(\mathbf{p}_{n_2} + \mathbf{p}_\alpha\right)$$

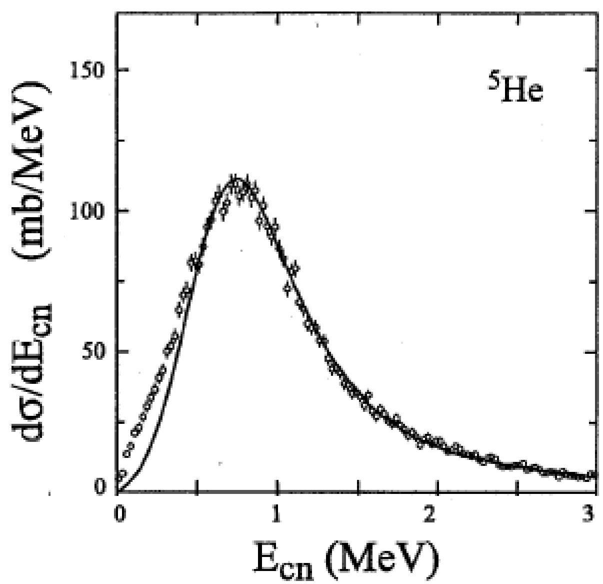
$$E_{\mathrm{fn}} = \frac{m_{\mathrm{f}} + m_{\mathrm{n}}}{2 m_{\mathrm{f}} m_{\mathrm{n}}} \mathbf{p}_{\mathrm{fn}}^2$$

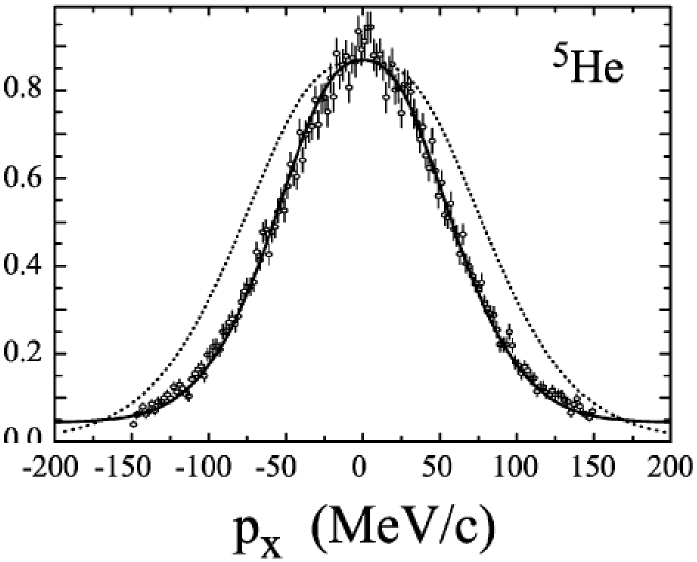
^3He	^4He	^5He	^6He	^7He	^8He	^9He	^{10}He
		unbound	808 ms	unbound	119 ms	unbound	unbound

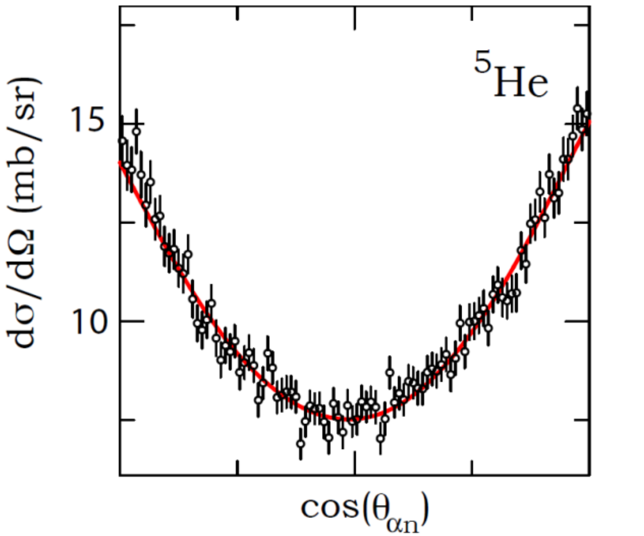


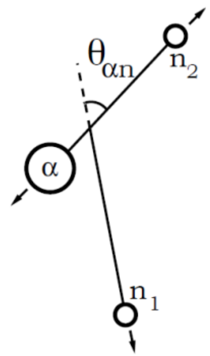
$$^6\mathrm{He} : {}^4\mathrm{He}\ \text{Ä}\ (n\mathrm{p}_{3/2})^2$$

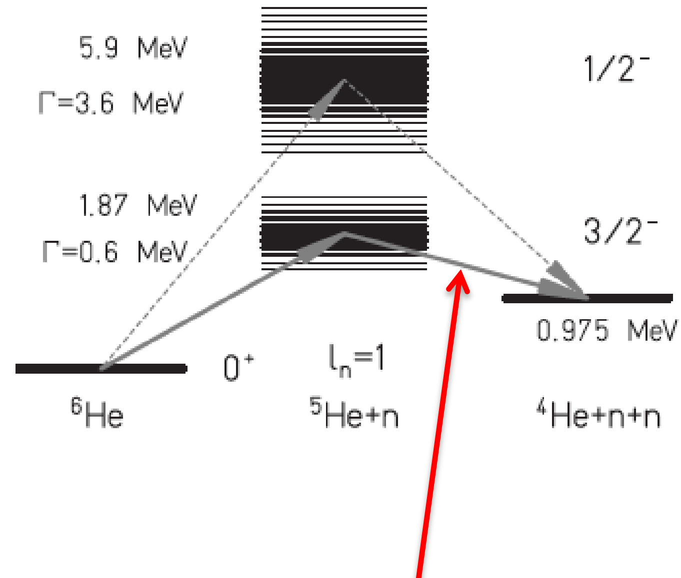
$$\mathbf{p}_{n_1} = -\left(\mathbf{p}_{n_2} + \mathbf{p}_{\alpha}\right)$$







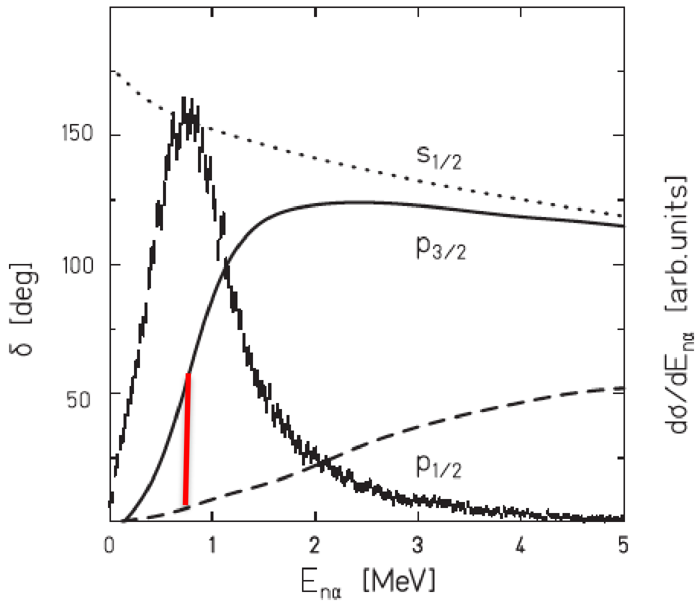




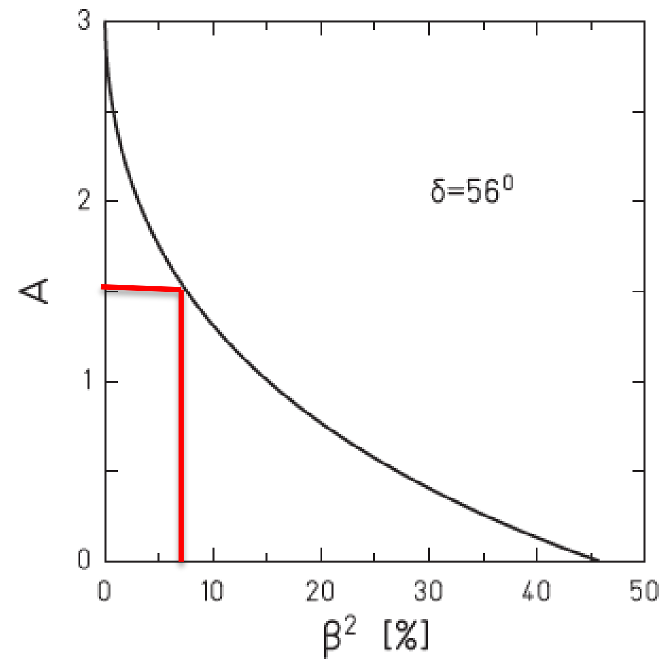
L.V. Chulkov *et al.*, PRL **79** (1997) 201

$$W(\theta_{\alpha n}) = 1 + 1.5(3)\cos^2(\theta_{\alpha n})$$

$$W(\theta_{\alpha n}) = 1 + 3\cos^2(\theta_{\alpha n})$$



Morgan, G.L., Walter, R.L.: Phys. Rev. **168**, 1114 (1968)



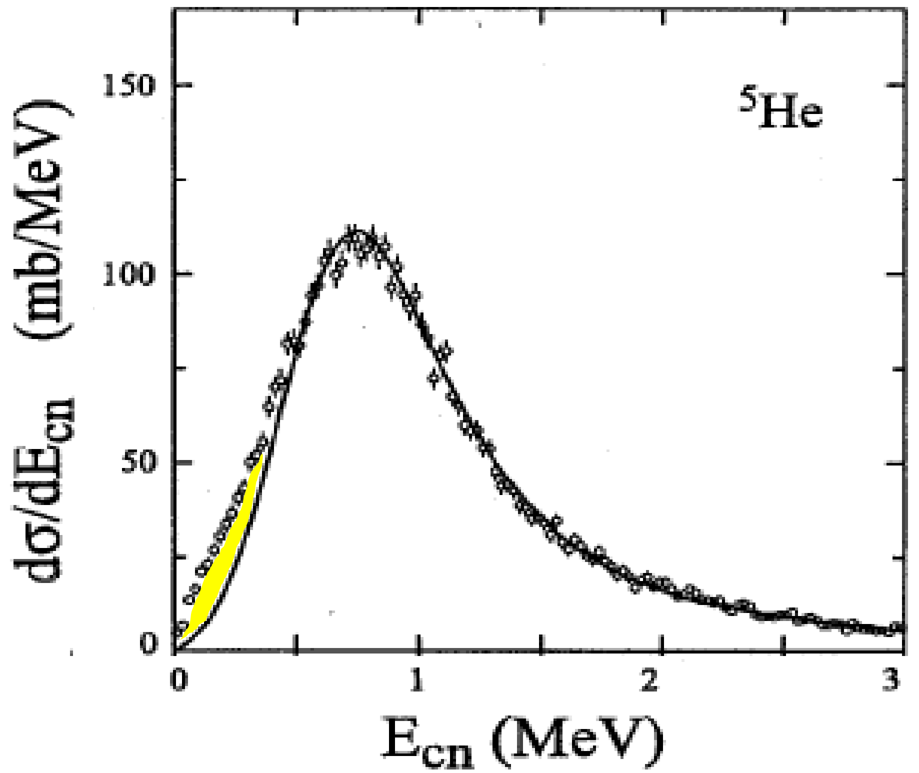
$$\frac{d\sigma}{d\cos(\vartheta_{n\alpha})} \sim \sum_{\nu_1,\nu_2} \left|\alpha f_{\nu_1,\nu_2}(3/2) + \beta e^{i\delta} f_{\nu_1,\nu_2}(1/2)\right|^2$$

$$\alpha^2 + \beta^2 = 1$$

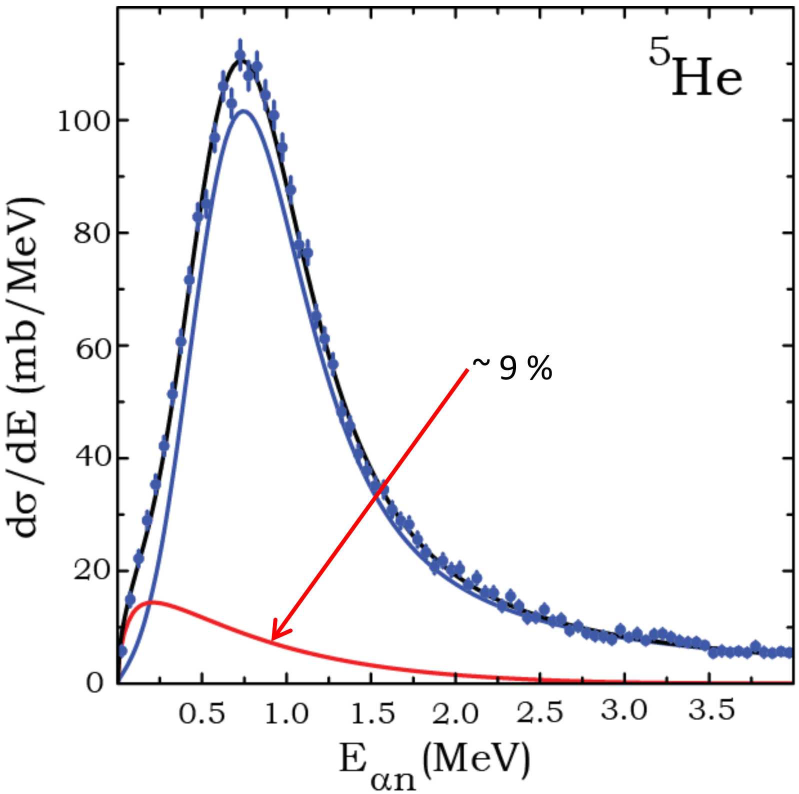
$$W(\theta_{\alpha n}) = 1 + 1.5(3)\cos^2(\theta_{\alpha n})$$

$(p_{1/2})^2 \sim 7\ \%$

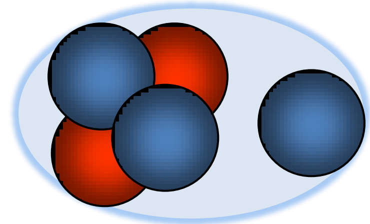
L.V. Chulkov, G. Schrieder, Z. Phys **A359** (97) 231



$$d\sigma / dE_{fn} \propto \frac{\Gamma_l(E_{fn})}{[E_r + \Delta_l(E_{fn}) - E_{fn}]^2 + \frac{1}{4}\Gamma_l^2(E_{fn})}$$



Yu. Aksyutina et al., PLB **679** (2009) 191



$$d\sigma / dE_{fn} \propto \frac{\Gamma_l(E_{fn})}{[E_r + \Delta_l(E_{fn}) - E_{fn}]^2 + \frac{1}{4}\Gamma_l^2(E_{fn})}$$

s-wave: Effective-range approximation

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

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

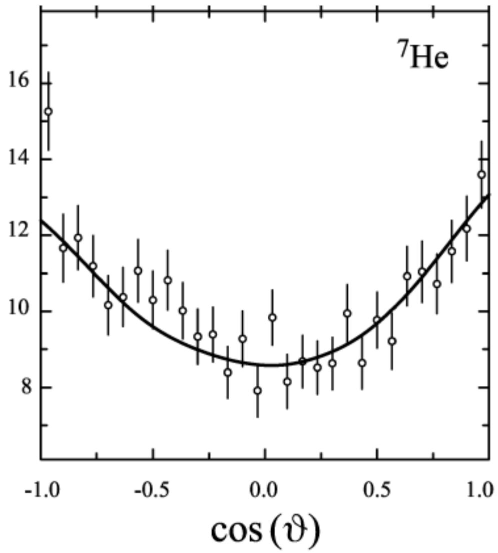
Bertch *et al.*, PRC **57** (1998) 1366

$$k = \sqrt{2\mu\varepsilon}$$
$$\varepsilon = 0.94(23)\,MeV$$
$$a = 3.37(38)\,fm$$

$\varepsilon \approx S_{2n}$

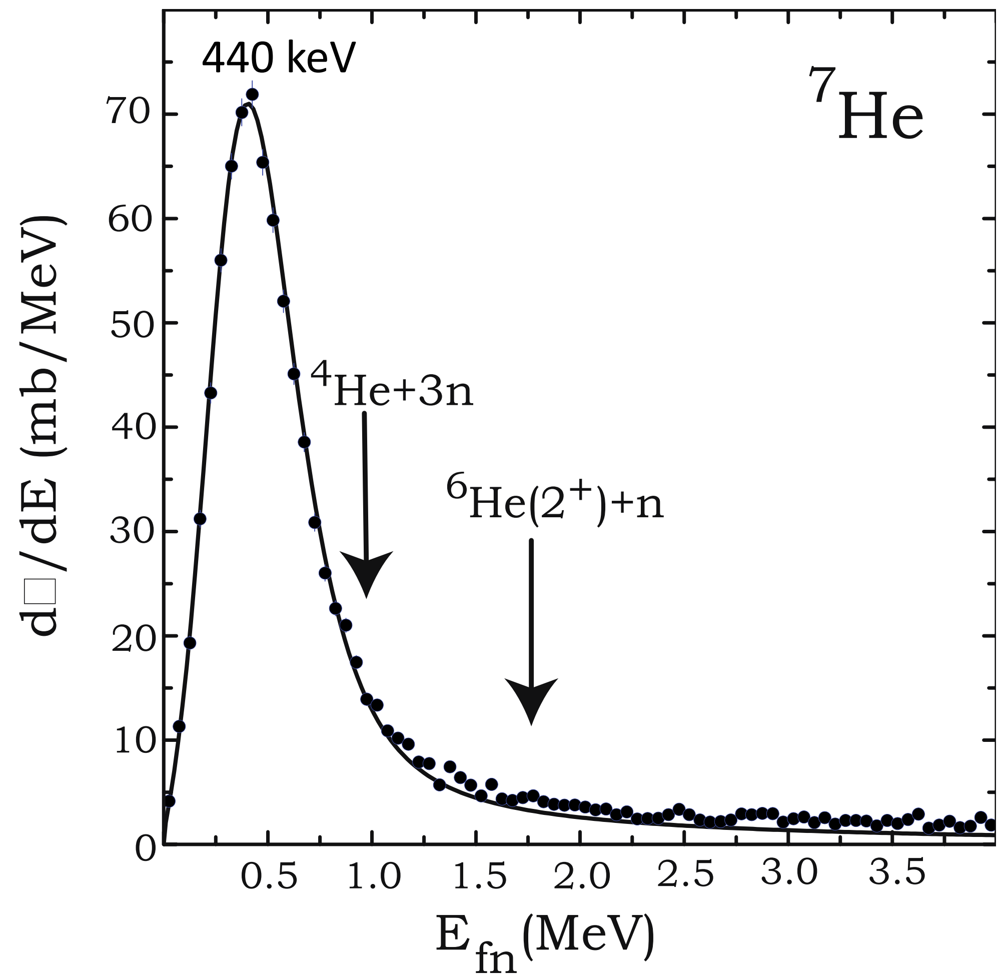
$(p_{3/2})^2$ ~ 86 %
$(p_{1/2})^2$ ~ 5 %
$(s_{1/2})^2$ ~ 7 %

B.V. Danilin et al., NPA **632** (98) 383

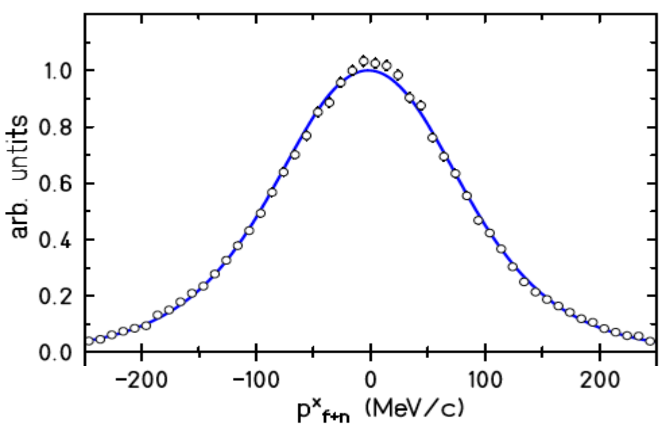


K. Markenroth *et al.*, NP **A679** (2001) 462

$$W(\vartheta_{^6\mathrm{He-n}}) \sim 1 + 0.7(1)\cos^2(\vartheta_{^6\mathrm{He-n}})$$



Yu. Aksyutina *et al.*,
PLB **679** (2009) 191



$$\frac{d\sigma}{dE_{\mathrm{fn}}} \propto \frac{\Gamma_l(E_{\mathrm{fn}})}{[E_r + \Delta_l(E_{\mathrm{fn}}) - E_{\mathrm{fn}}]^2 + \frac{1}{4}\Gamma_l^2(E_{\mathrm{fn}})}$$

$$\Gamma_l = 2P_l(E_{\mathrm{fn}})\gamma^2$$

$$\gamma_{\mathrm{sp}}^2 = \frac{2}{3}\hbar^2/\mu R^2$$

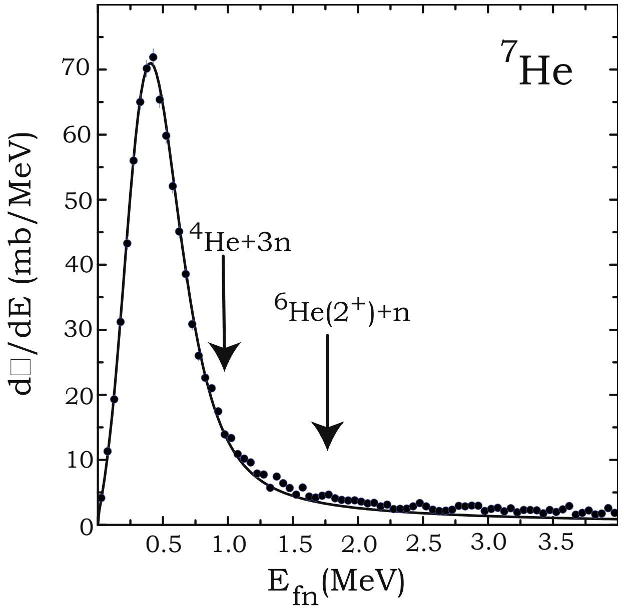
$$\mathcal{S}_{\mathrm{n}} = \gamma_{\mathrm{obs}}^2/\gamma_{\mathrm{sp}}^2$$

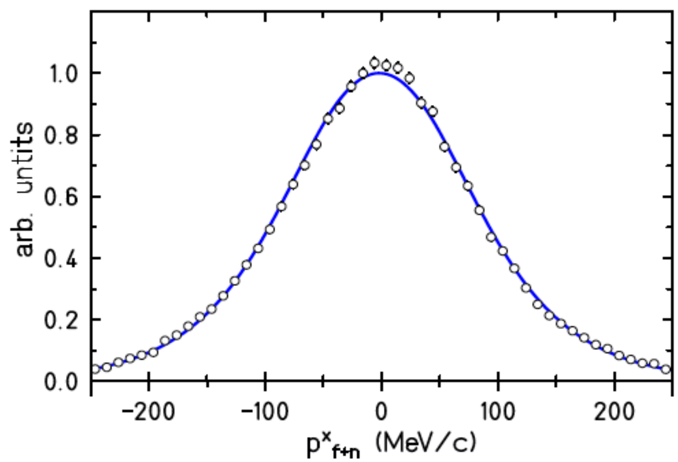
Yu. Aksyutina *et al.*,
PLB **679** (2009) 191

^{5}He $\quad \gamma_{\mathrm{obs}}^2 = \gamma_{\mathrm{sp}}^2$

^{7}He: ^{6}He(0^+) + n $\quad \mathcal{S}_{\mathrm{n}} = 0.61(3)$

→ not a pure single-particle $p_{3/2}$-state





Momentum Profile Function

$$P(E_{fn}) = \sqrt{\left\langle (p_f^x + p_n^x)^2 \right\rangle - \left\langle (p_f^x + p_n^x) \right\rangle^2}$$

Transverse Momentum Distribution

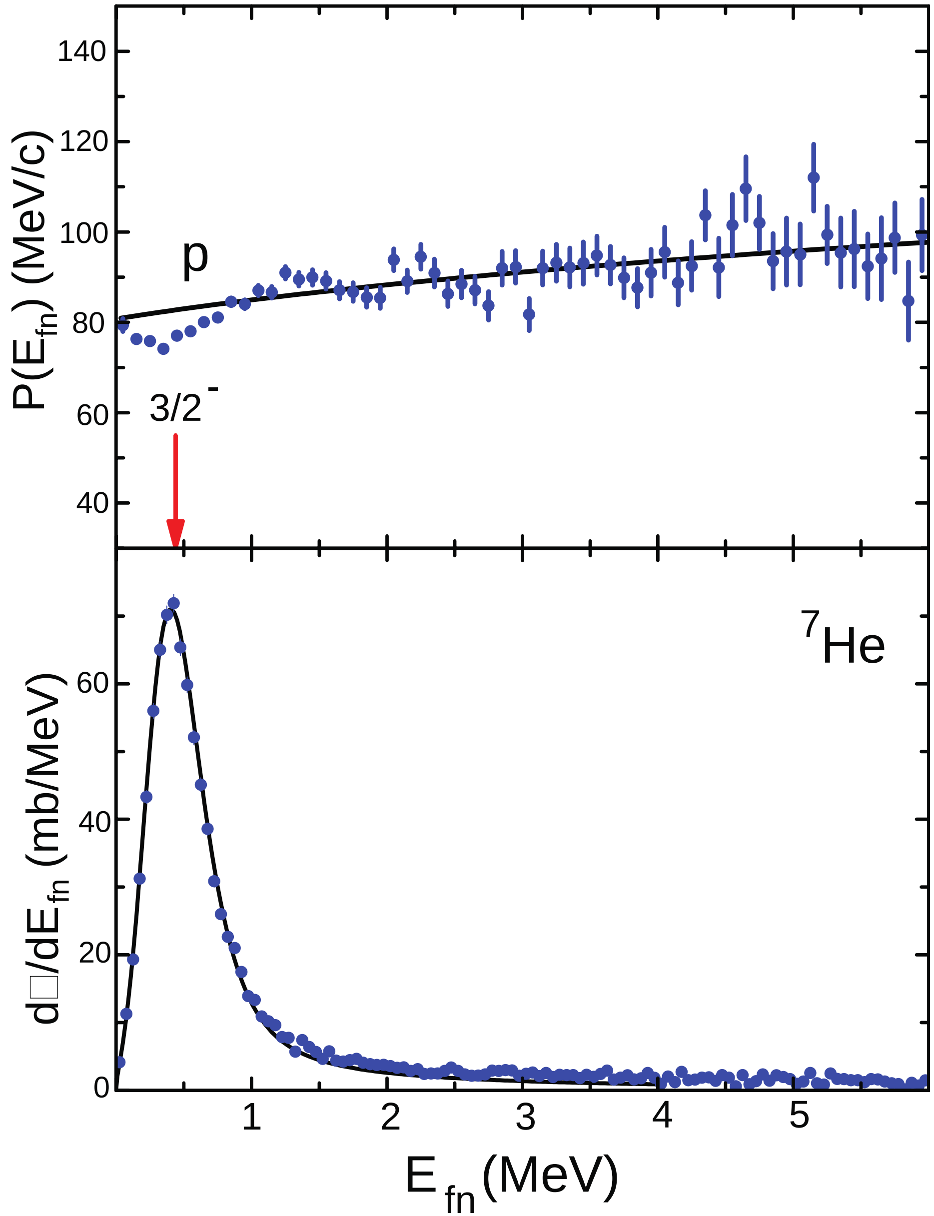
$$\frac{d\sigma_0}{dk_z} = \frac{\sigma_T B^2 \kappa b_{\min}^2}{2\pi}[K_1^2 - K_0^2]$$

$$\frac{d\sigma_1}{dk_z} = \frac{\sigma_T B^2 b_{\min}^2}{2\pi\kappa}\Big[k_z^2(K_1^2 - K_0^2) + (k_z^2 + \kappa^2) \times \left(K_2^2 - K_1^2 - \frac{2}{\xi}K_1 K_2\right)\Big]$$

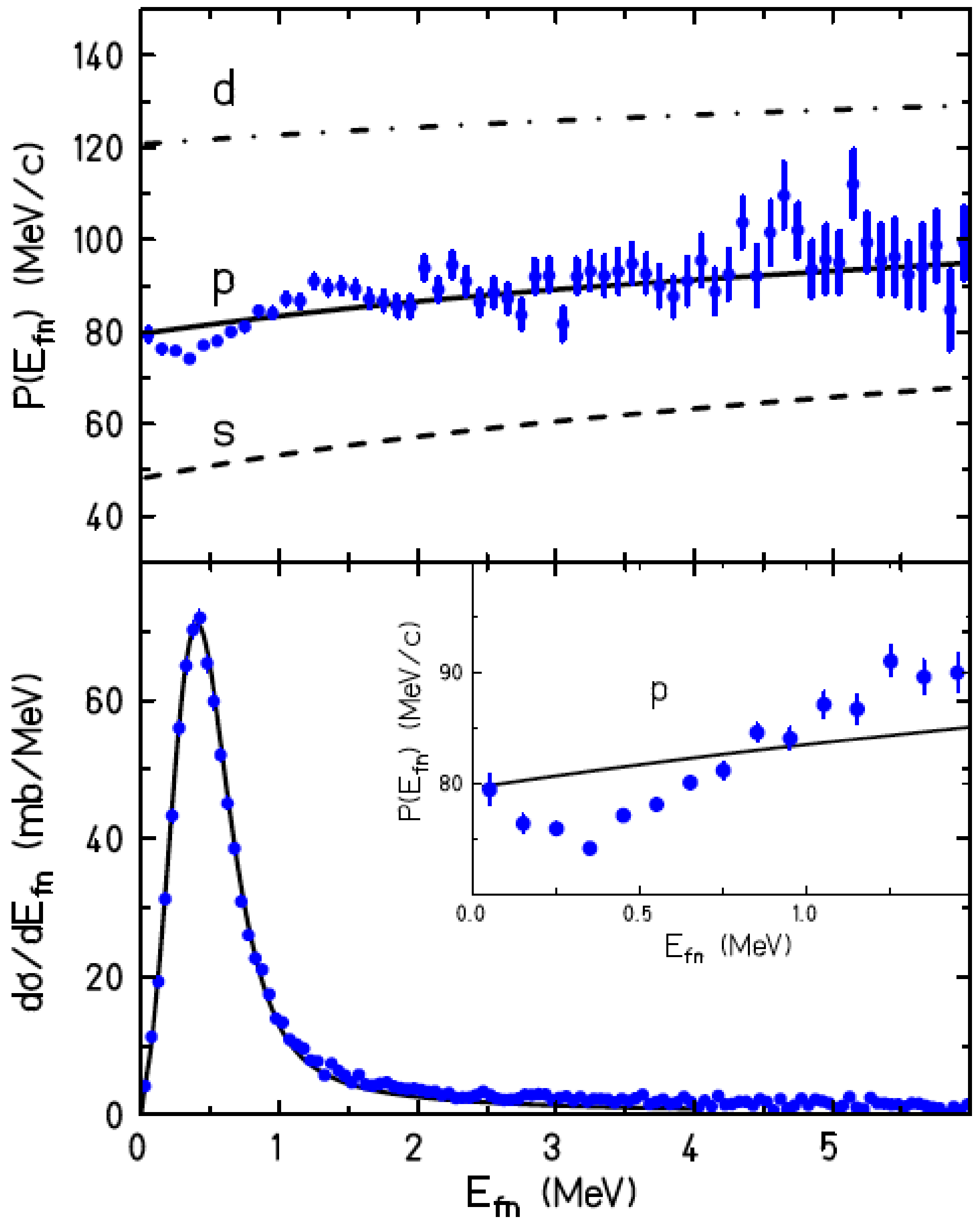
$$\xi = b_{\min}\sqrt{\kappa^2 + k_z^2}$$

$$\kappa = (2\mu S_n)^{1/2}/\hbar$$

P.G. Hansen, PRL **77** (1996) 1016
D. Basin et al., Phys. Rev. C **57** (1998) 2156



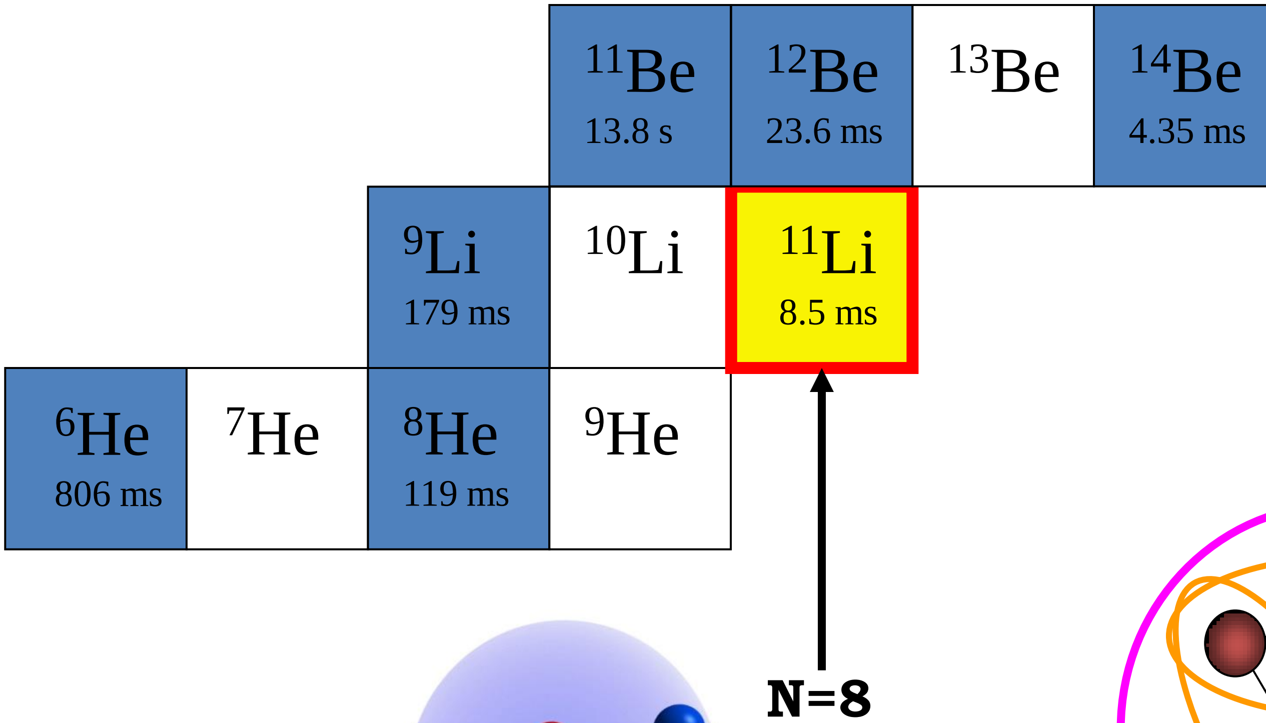
Yu. Aksyutina *et al.*,
PLB **718** (2013) 1309



$$P_{r.e.}(E_{fn}) = \sqrt{\alpha_s \sigma_s^2 + (1-\alpha_s)\sigma_p^2}$$

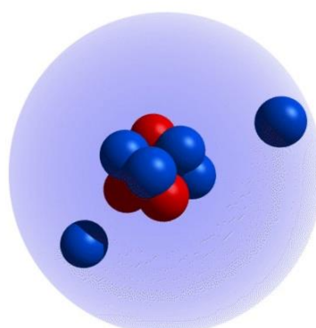
$l = 0$ $l = 1$

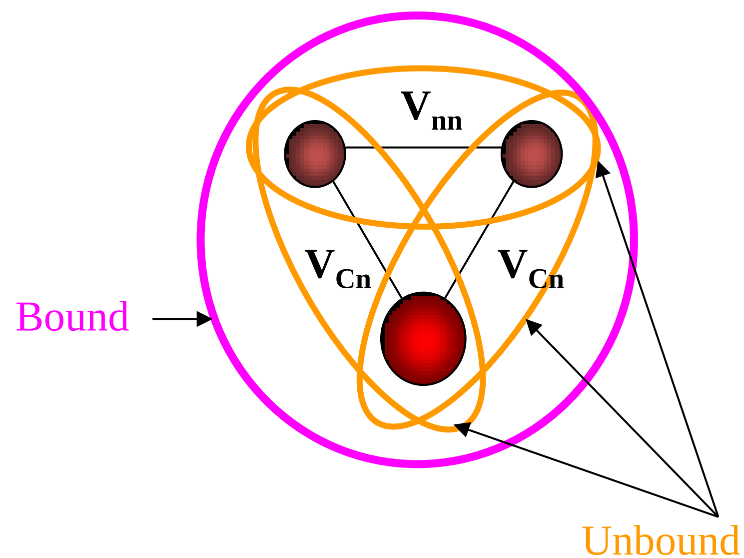
$12\%\ (1s_{1/2})^2$



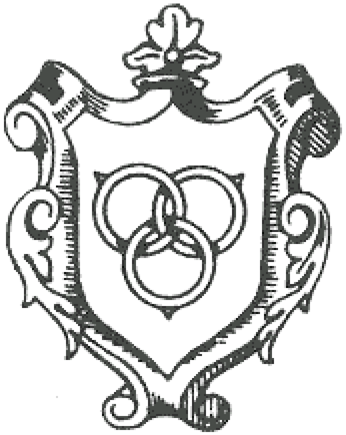
^{11}Li

S_n=369 keV

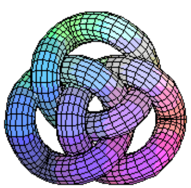


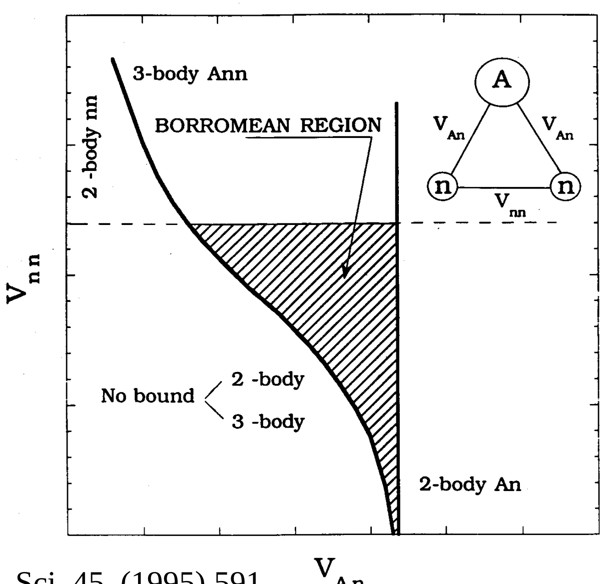


BORROMEAN



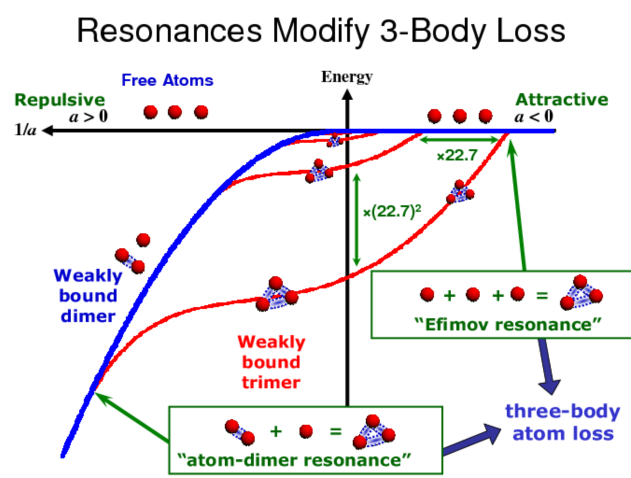
M.V. Zhukov *et al*. Phys. Rep. 231 (1993) 151





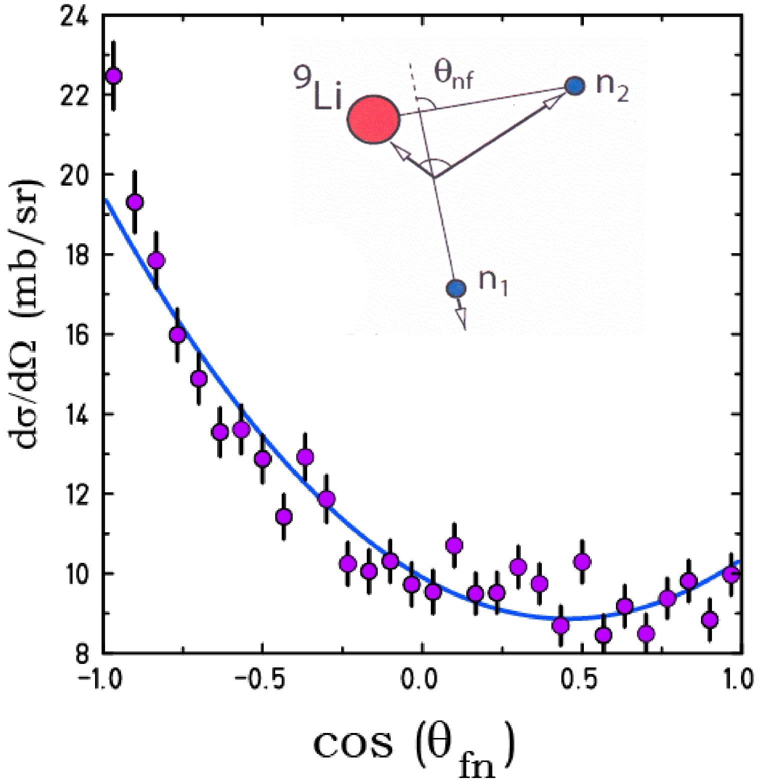
P.G. Hansen *et al*.

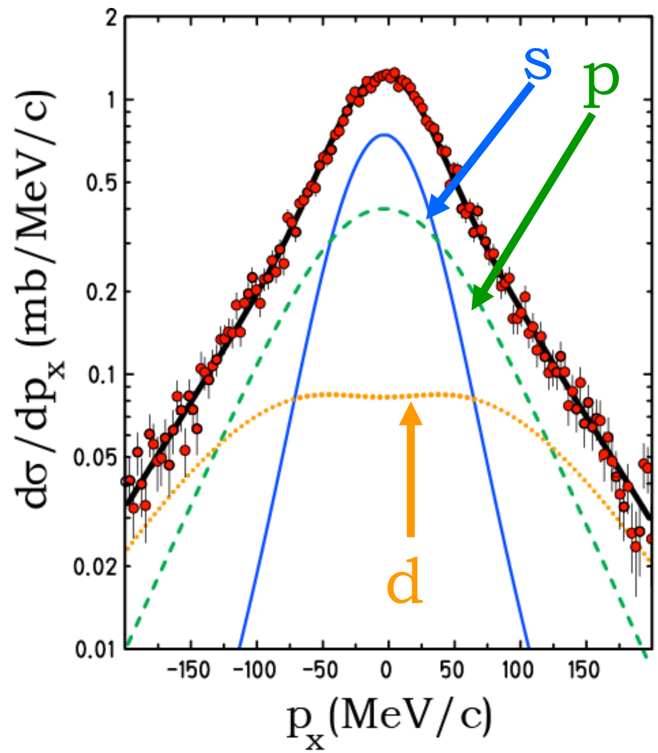
Ann.Rev.Nucl.Part. Sci. 45 (1995) 591



S.E. Pollack *et al*. Science 326 (2009) 1683

GSI, 287 MeV/u ^{11}Li



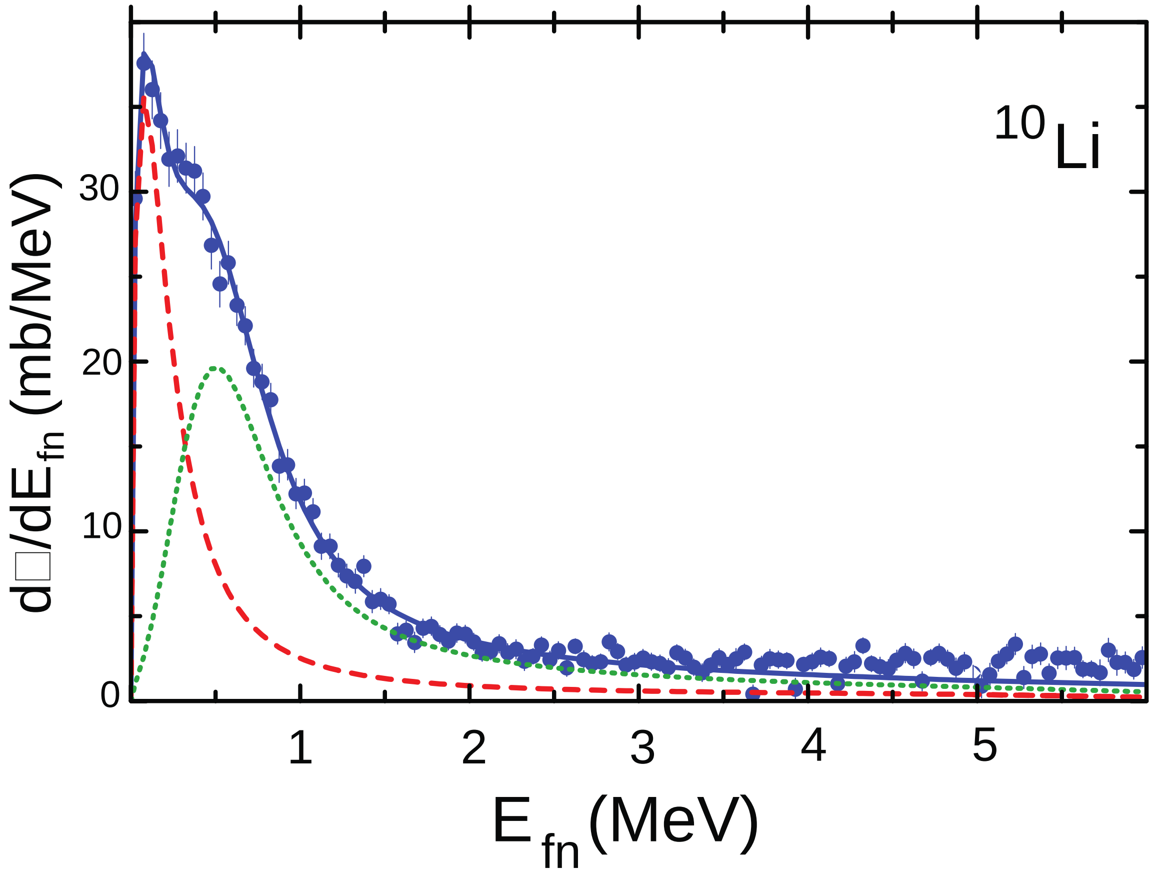


$W(\theta_{nf}) = 1\text{-}1.03\cos(\theta_{nf}) + 1.41\cos^2(\theta_{nf})$

$\mathbf{p}_{n1} = -(\mathbf{p}_{n2} + \mathbf{p}_{9Li})$

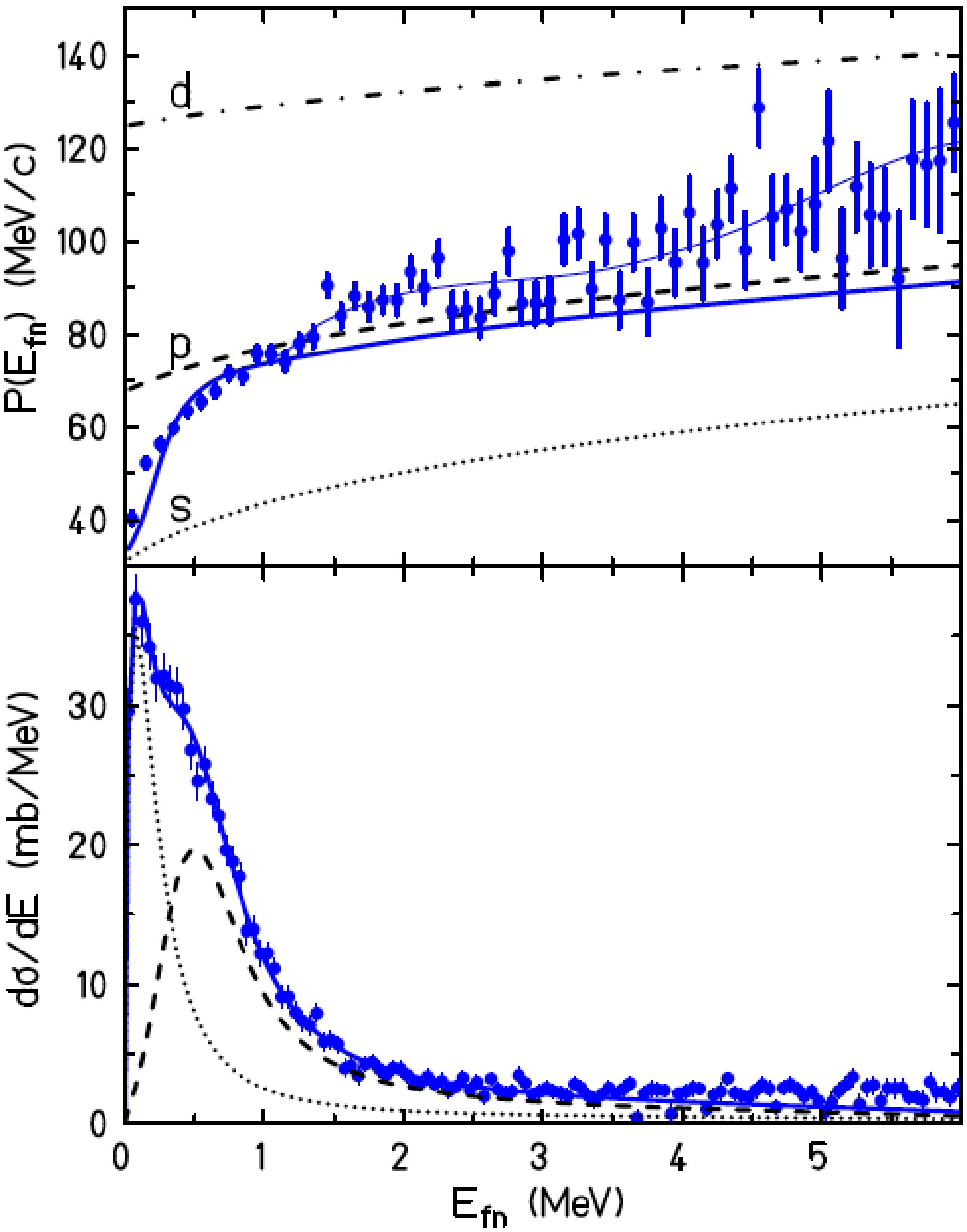
$(1s_{1/2})^2 \quad (0p_{1/2})^2$

Simon, *et al.*, Nucl. Phys. **A791** (2007) 267.



Momentum Profile Function

$$P(E_{fn}) = \sqrt{\left\langle (p_f^x + p_n^x)^2 \right\rangle - \left\langle (p_f^x + p_n^x) \right\rangle^2}$$



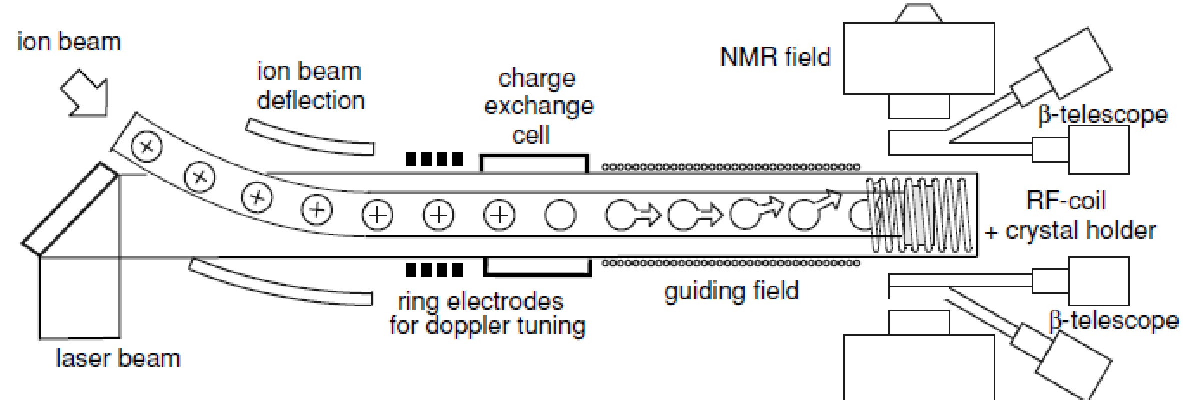
$$P_{r.e.}(E_{fn}) = \sqrt{\alpha_s \sigma_s^2 + (1-\alpha_s)\sigma_p^2}$$

$$\alpha_d = (P_{exp}^2 - P_{r.e.}^2)/(\sigma_d^2 - P_{r.e.}^2)$$

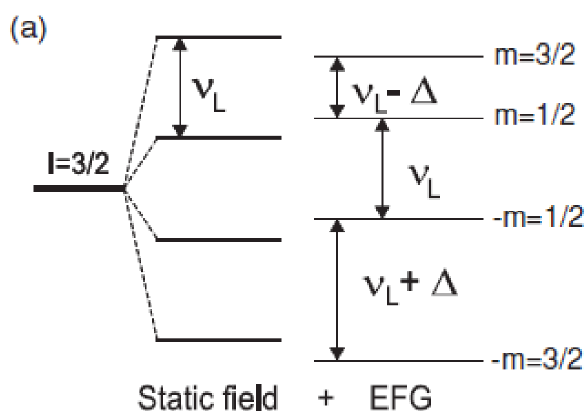
$(0d_{5/2})^2$
11(2) %

Aksyutina *et al.*
PLB **718** (2013) 1309

^{6}Li	^{7}Li	^{8}Li	^{9}Li	^{10}Li	^{11}Li	^{12}Li	^{13}Li
		840 ms	179 ms	unbound	8.5 ms	unbound	unbound
			$I^{\pi}=3/2^{-}$		$I^{\pi}=3/2^{-}$		



D. Borremans et al., PRC 72 (2005) 044309



Si [LiF] → $\mu(^{11}\text{Li}) = 3.6712(3)\ \mu_N$

Zn [$LiNbO_3$] → $|Q(^{11}\text{Li})| = 33.3(5)$ mb

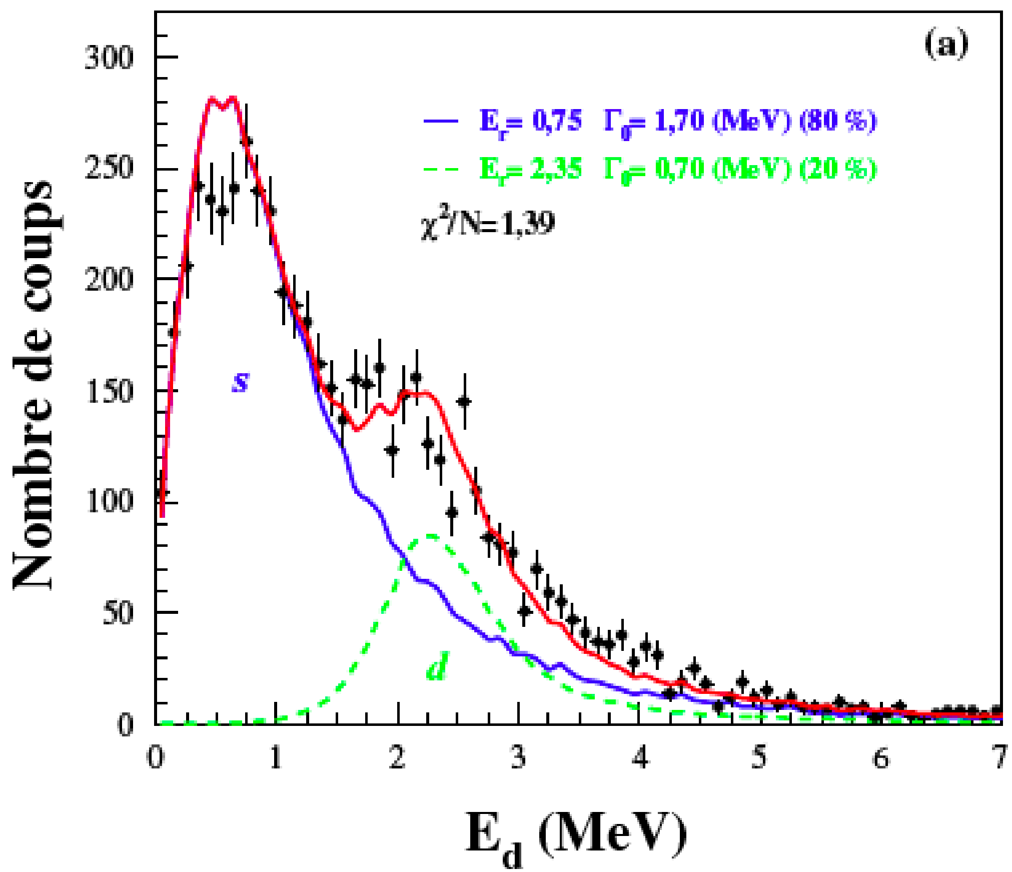
R. Neugart et al., PRL **101**(2008) 132502

$|Q(^{11}\text{Li})/Q(^{9}\text{Li})| = 1.088(15)$

^{7}Be	^{8}Be	^{9}Be	^{10}Be	^{11}Be	^{12}Be	^{13}Be	^{14}Be	^{15}Be	^{16}Be
	unbound		1.6 10^{6} y	13.8 s	23.6 ms	unbound	4.35 ms	unbound	unbound

GANIL

41 MeV/u ^{14}B, C target



J.L. Lecouey, Few Body Systems 34 (2004)21
G. Randisi, Thesis Uni. Caen (2011)

^{16}Be

Spyrou *et al.*,, PRL 108(2012) 102501

^{15}Be

Snyder *et al.*,, PRC 88(2013) 031303

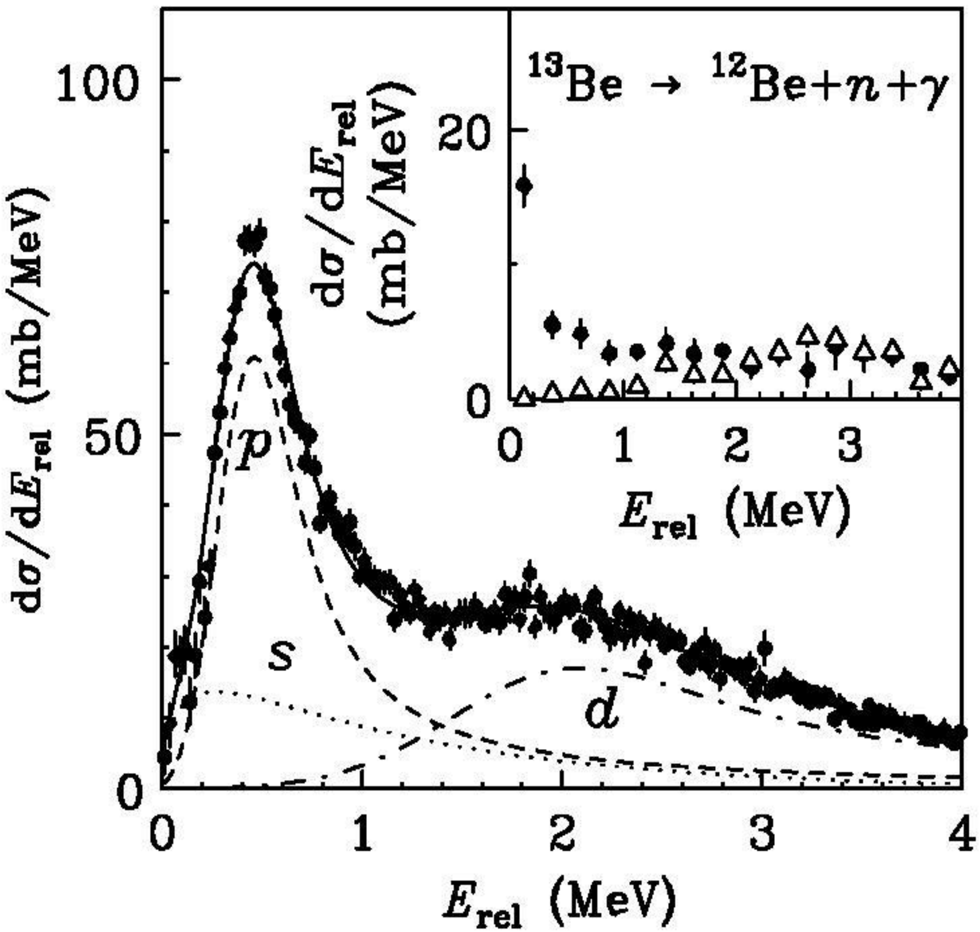
		^{17}B 5.1 ms
^{14}Be 4.35 ms	^{15}Be unbound	^{16}Be unbound

^{14}B

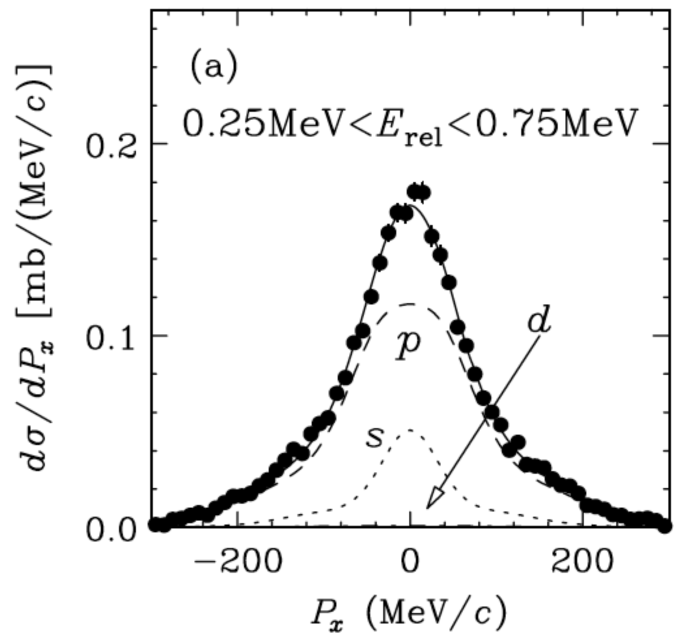
$$^{13}B(3/2^-) \otimes (sd)$$

RIKEN

69 MeV/u ^{14}Be, Lq H target

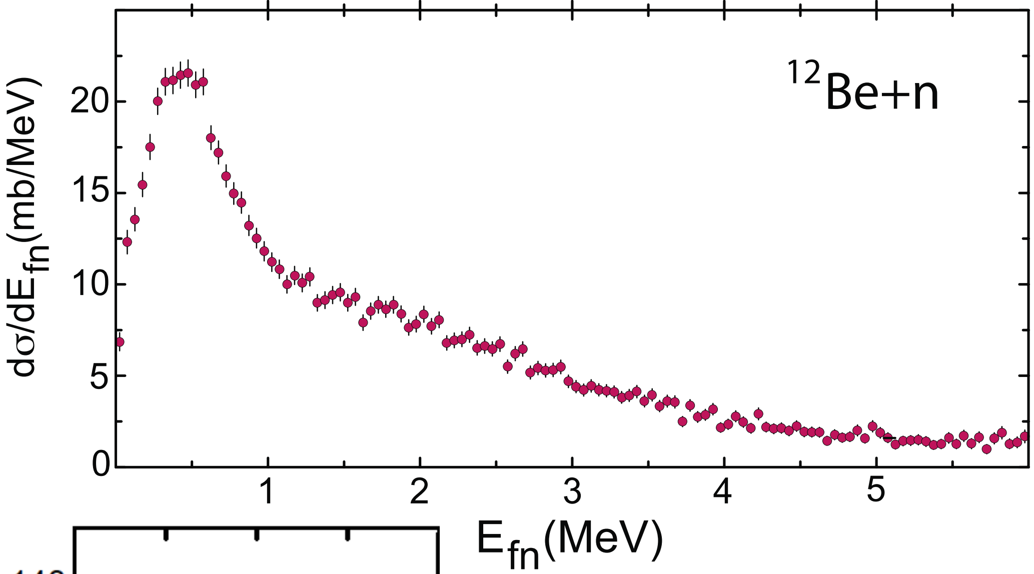


Y. Kondo *et al.*, PLB **690** (2010) 245

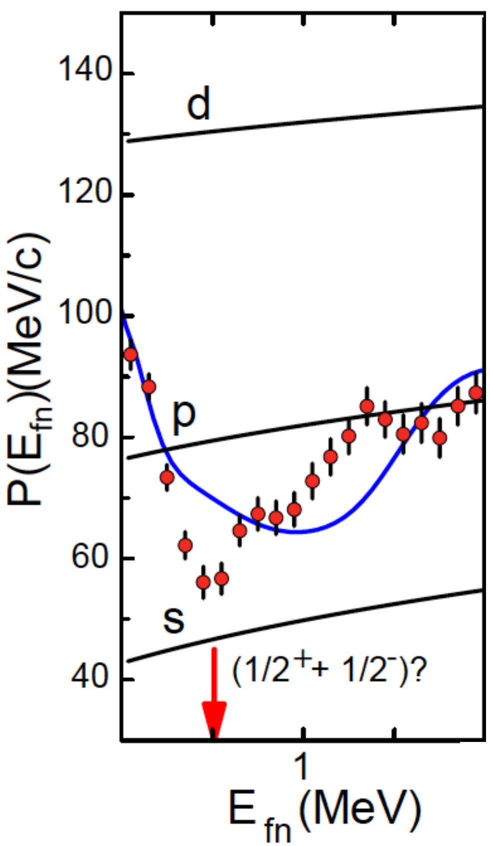


n - *g coincidences*

2.11 *MeV and* 2.71 *MeV*

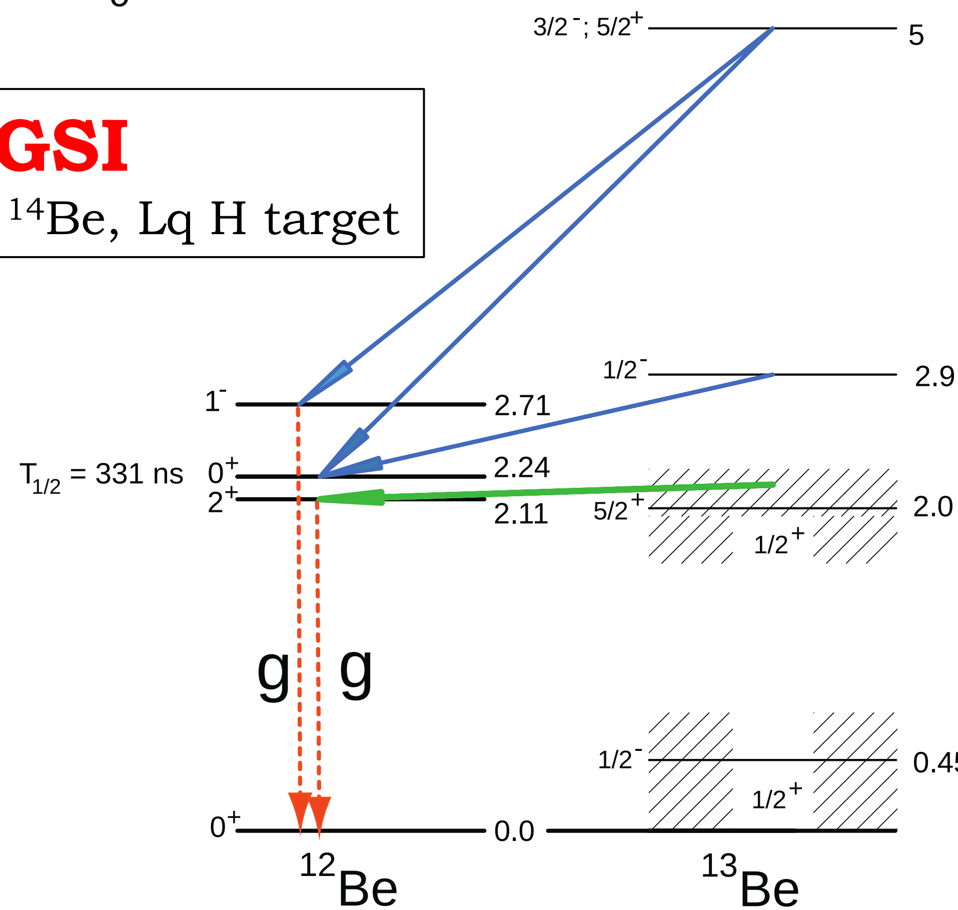


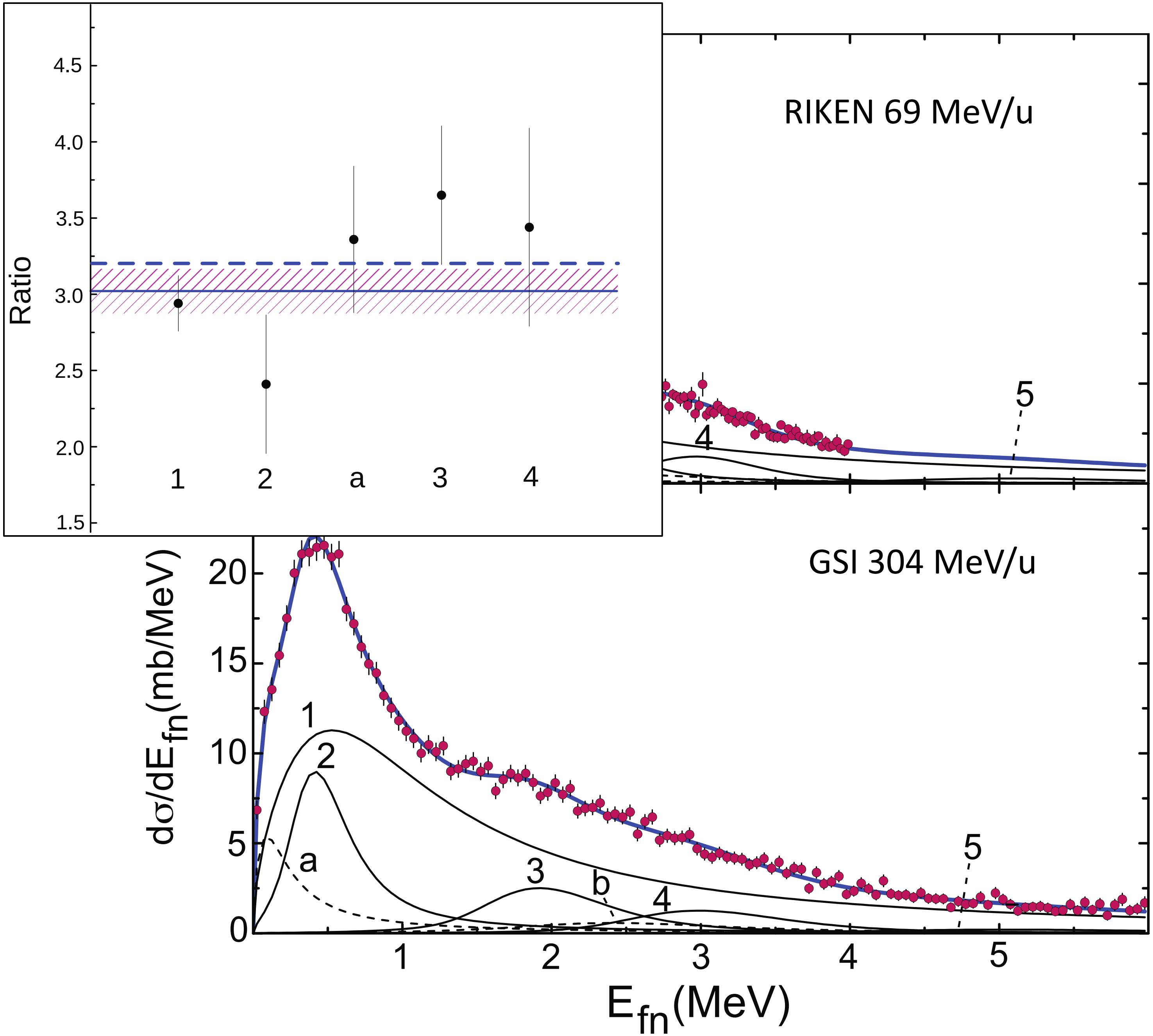
Yu. Aksyutina *et al.*,
Phys. Rev. C **87** (2013) 064316



GSI

304 MeV/u ^{14}Be, Lq H target





$$\frac{s_{69}}{s_{304}} = 3.2$$

INTERFERENCE ?

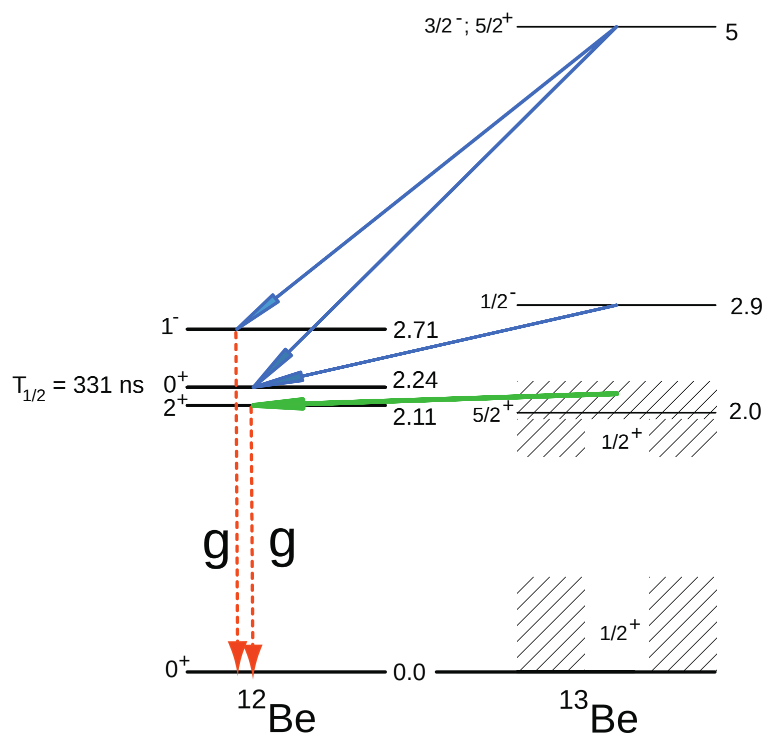
$$^{12}\mathrm{Be}(0^+) = \alpha[^{10}\mathrm{Be} \otimes (1s_{1/2})^2] + \beta[^{10}\mathrm{Be} \otimes (0p_{1/2})^2] + \gamma[^{10}\mathrm{Be} \otimes (0d_{5/2})^2],$$

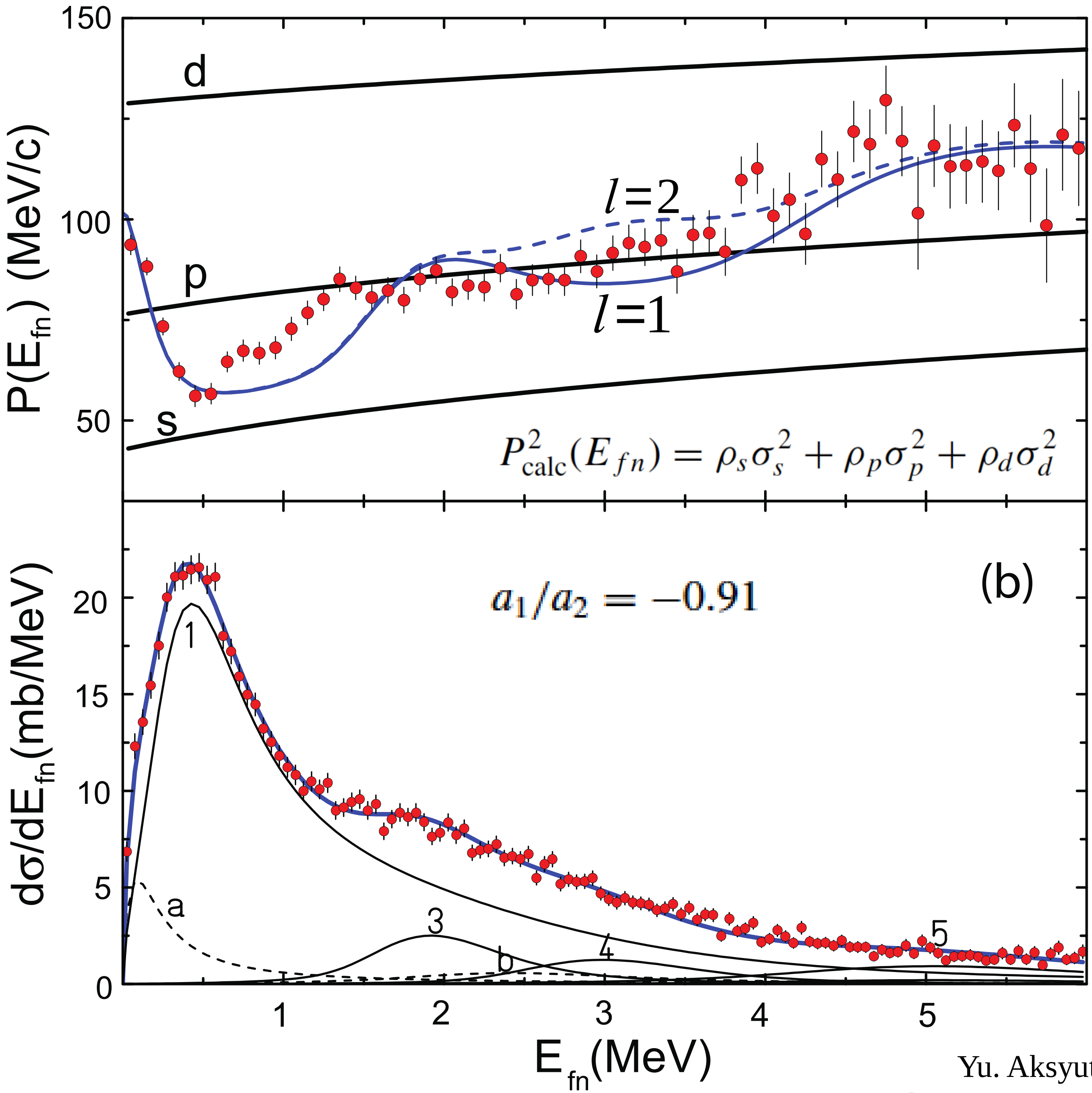
a^2=0.35, b^2=0.31, g^2 =0.34

$$^{13}\mathrm{Be}(1/2_2^+) = \mu[^{10}\mathrm{Be} \otimes (0p_{1/2})^2 \otimes (1s_{1/2})] - \lambda[^{10}\mathrm{Be} \otimes (0d_{5/2})^2 \otimes (1s_{1/2})]$$

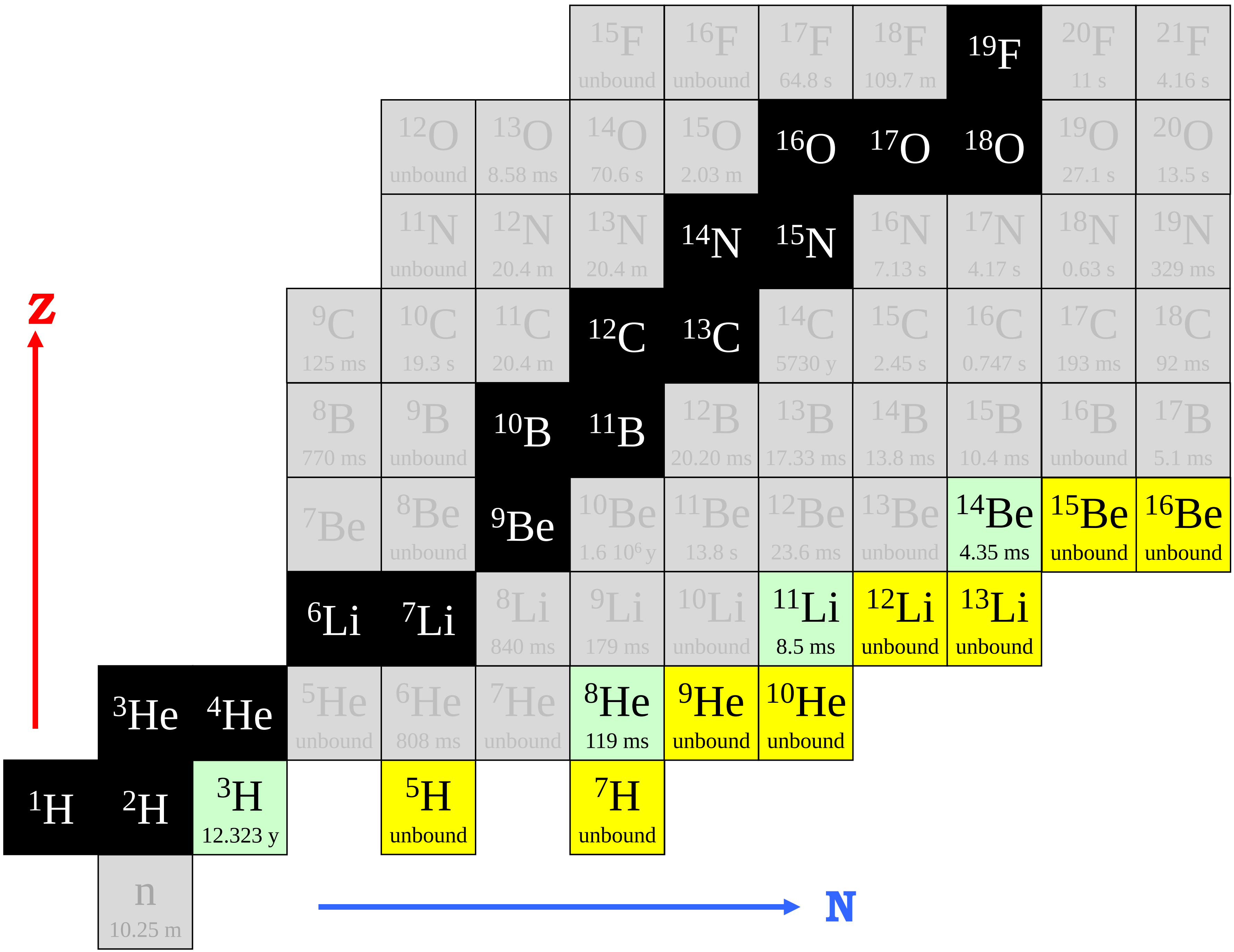
$$^{13}\mathrm{Be}(1/2_1^+) = \lambda[^{10}\mathrm{Be} \otimes (0p_{1/2})^2 \otimes (1s_{1/2})] + \mu[^{10}\mathrm{Be} \otimes (0d_{5/2})^2 \otimes (1s_{1/2})].$$

$$d\sigma/dE_{fn} \propto \sqrt{E_{fn}}\left|\frac{a_1}{E_1 - E_{fn} - i\Gamma_1/2} + \frac{a_2}{E_2 - E_{fn} - i\Gamma_2/2}\right|^2,$$





Yu. Aksyutina *et al.*,
Phys. Rev. C **87** (2013) 064316



Z
^{15}F unbound
^{16}F unbound
^{17}F 64.8 s
^{18}F 109.7 m
^{19}F
^{20}F 11 s
^{21}F 4.16 s
^{12}O unbound
^{13}O 8.58 ms
^{14}O 70.6 s
^{15}O 2.03 m
^{16}O
^{17}O
^{18}O
^{19}O 27.1 s
^{20}O 13.5 s
^{11}N unbound
^{12}N 20.4 m
^{13}N 20.4 m
^{14}N
^{15}N
^{16}N 7.13 s
^{17}N 4.17 s
^{18}N 0.63 s
^{19}N 329 ms
^{9}C 125 ms
^{10}C 19.3 s
^{11}C 20.4 m
^{12}C
^{13}C
^{14}C 5730 y
^{15}C 2.45 s
^{16}C 0.747 s
^{17}C 193 ms
^{18}C 92 ms
^{8}B 770 ms
^{9}B unbound
^{10}B
^{11}B
^{12}B 20.20 ms
^{13}B 17.33 ms
^{14}B 13.8 ms
^{15}B 10.4 ms
^{16}B unbound
^{17}B 5.1 ms
^{7}Be
^{8}Be unbound
^{9}Be
^{10}Be 1.6 10^{6} y
^{11}Be 13.8 s
^{12}Be 23.6 ms
^{13}Be unbound
^{14}Be 4.35 ms
^{15}Be unbound
^{16}Be unbound
^{6}Li
^{7}Li
^{8}Li 840 ms
^{9}Li 179 ms
^{10}Li unbound
^{11}Li 8.5 ms
^{12}Li unbound
^{13}Li unbound
^{3}He
^{4}He
^{5}He unbound
^{6}He 808 ms
^{7}He unbound
^{8}He 119 ms
^{9}He unbound
^{10}He unbound
^{1}H
^{2}H
^{3}H 12.323 y
^{5}H unbound
^{7}H unbound
n 10.25 m
N

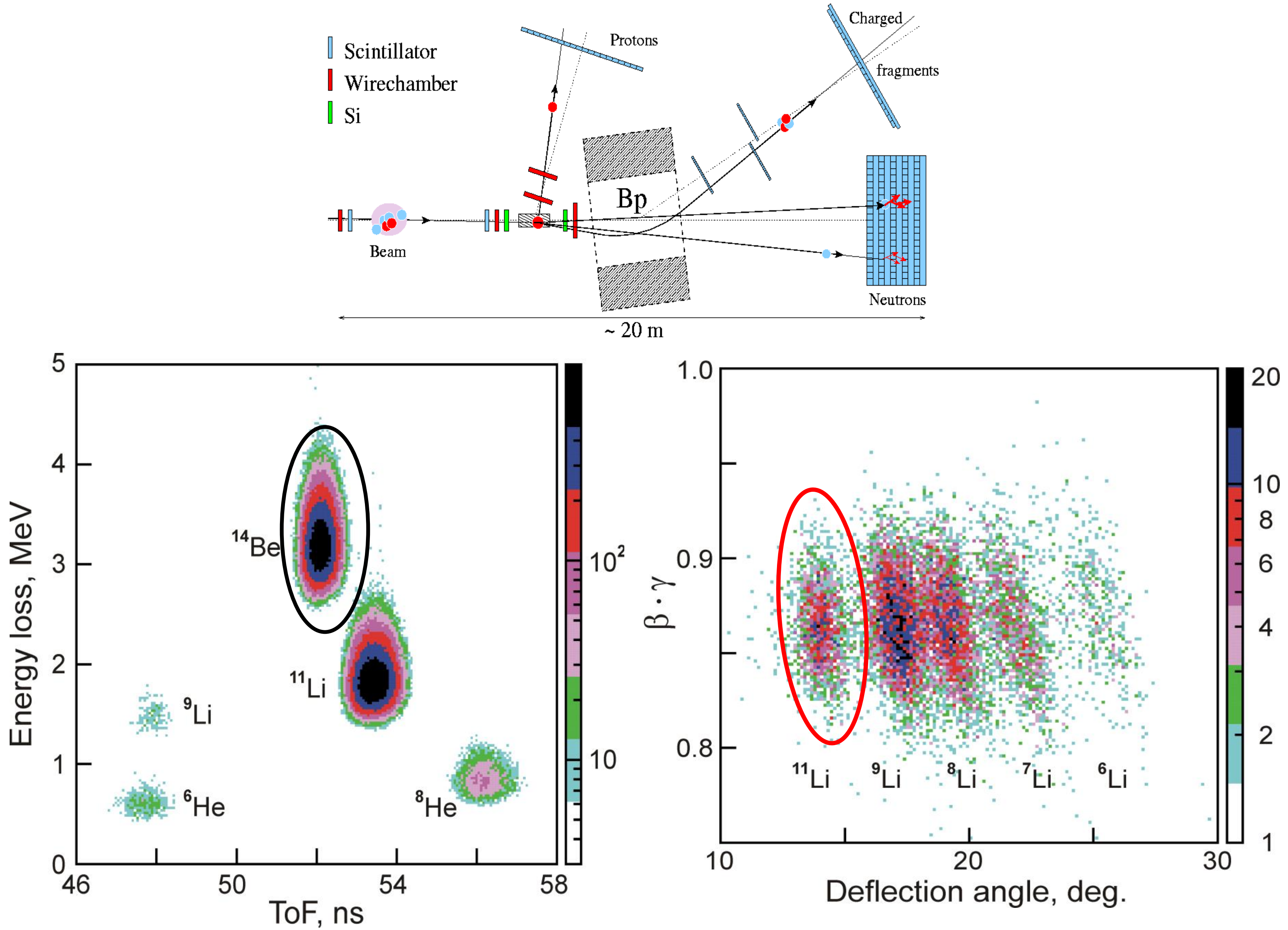
Dripline nuclei as stepping stones towards the unbound

	^{7}Be	^{8}Be unbound	^{9}Be	^{10}Be $1.6\ 10^{6}$ y	^{11}Be 13.8 s	^{12}Be 23.6 ms	^{13}Be unbound	^{14}Be 4.35 ms
	^{6}Li	^{7}Li	^{8}Li 840 ms	^{9}Li 179 ms	^{10}Li unbound	^{11}Li 8.5 ms	^{12}Li unbound	^{13}Li unbound
^{4}He	^{5}He unbound	^{6}He 808 ms	^{7}He unbound	^{8}He 119 ms	^{9}He unbound	^{10}He unbound		
				^{7}H unbound				

^{11}Li: Neutron knock-out reaction -> ^{10}Li
Proton knock-out reactions -> ^{9,10}He

^{14}Be: Neutron knock-out reaction -> ^{13}Be
Proton knock-out reactions -> ^{12,13}Li

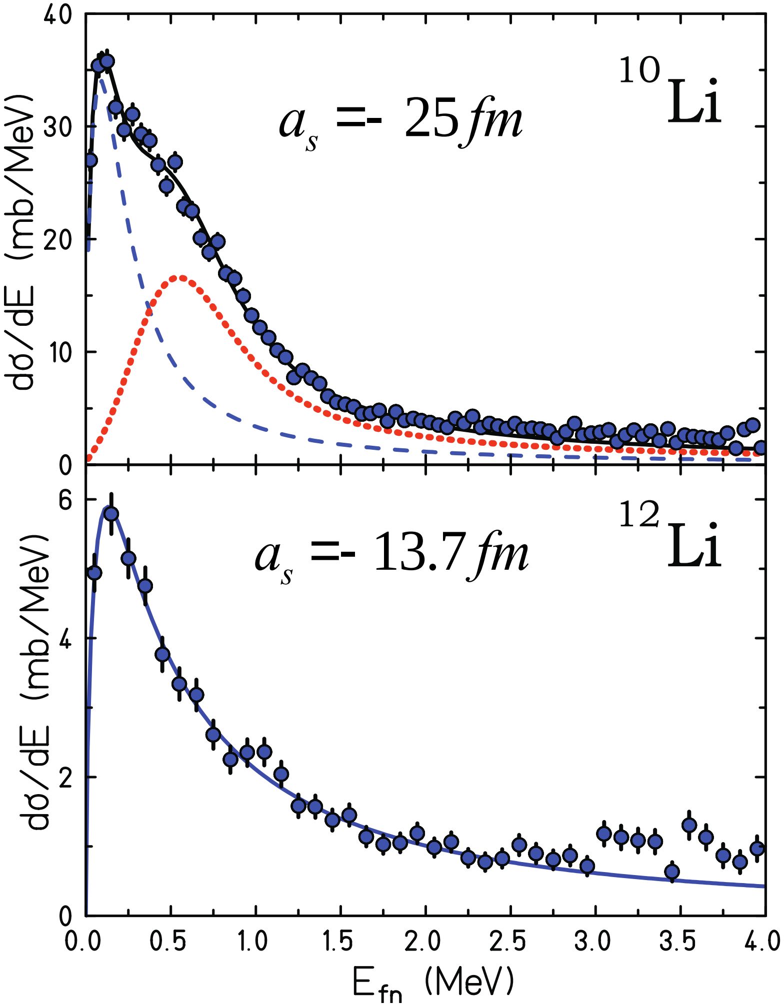
^{8}He: Neutron knock-out reaction -> ^{7}He
Proton knock-out reaction -> (^{7}H)

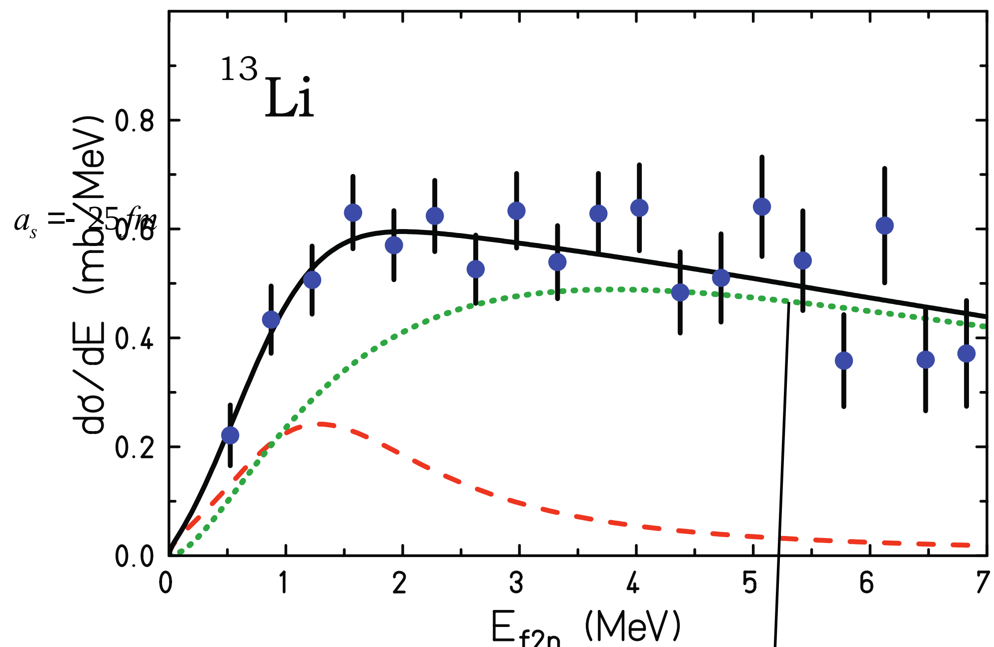


Scintillator
Wirechamber
Si
Protons
Charged
fragments
Bp
Beam
Neutrons
~ 20 m
Energy loss, MeV
ToF, ns
14Be
11Li
9Li
6He
8He
β·γ
Deflection angle, deg.
11Li
9Li
8Li
7Li
6Li

^{6}Li ^{7}Li	^{8}Li	^{9}Li	^{10}Li	^{11}Li	^{12}Li	^{13}Li
	840 ms	179 ms	unbound	8.5 ms	unbound	unbound

Yu. Aksyutina et al., Phys. Lett. **B 666** (2008) 430

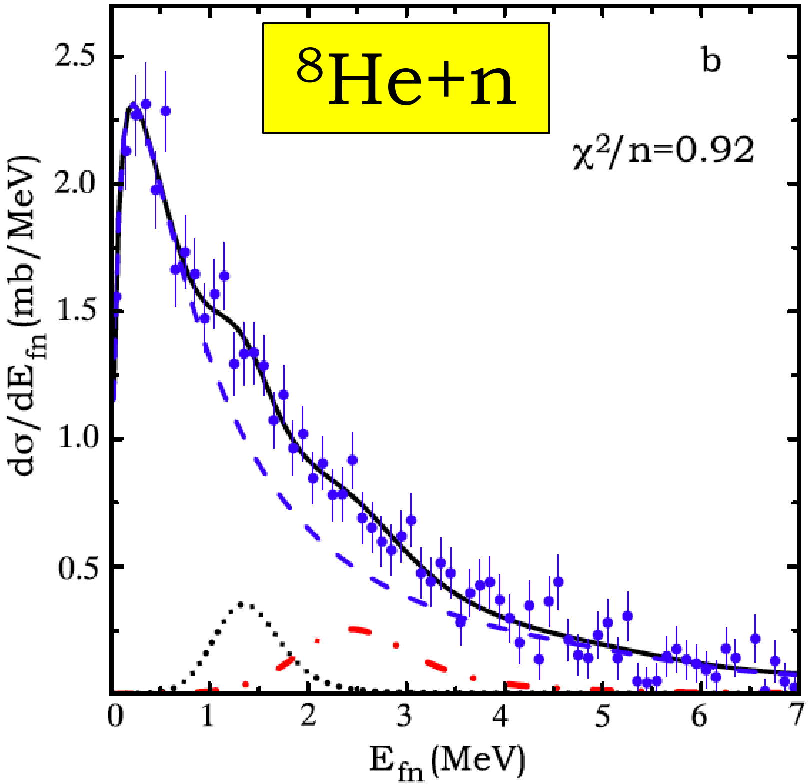




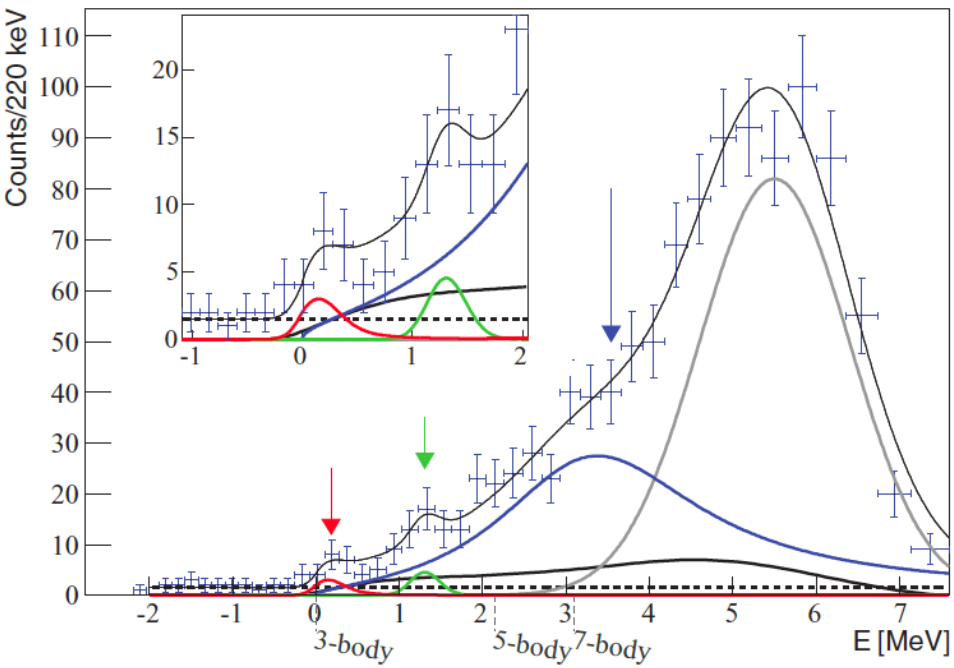
Forssén *et al*. Nucl. Phys. **A 673**(2000) 143

^3He	^4He	^5He	^6He	^7He	^8He	^9He	^{10}He
		unbound	808 ms	unbound	119 ms	unbound	unbound

$^8He(d,p)^9He$

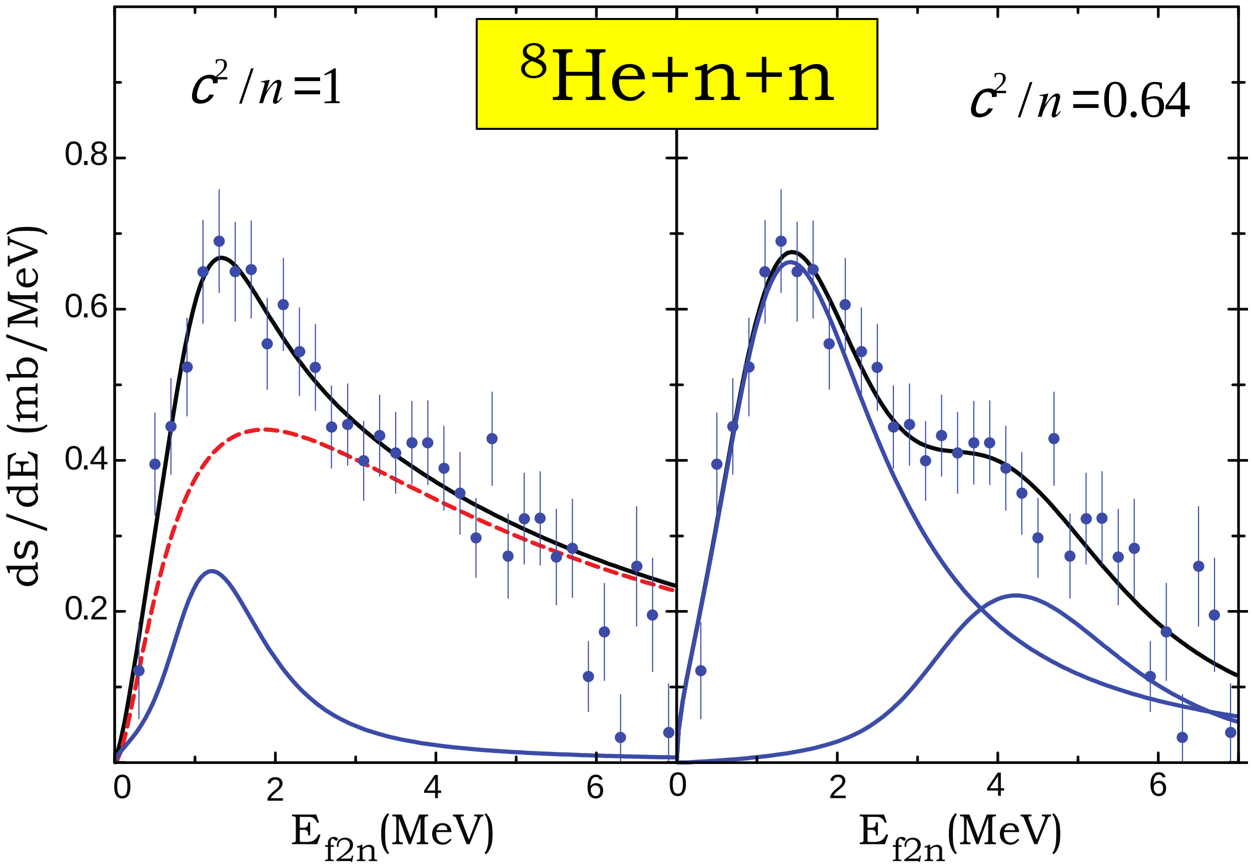


Johansson et al., Nucl. Phys. **A842** (2010) 15



Al Kalanee et al., PRC **88** (2013) 034301

^3He	^4He	^5He	^6He	^7He	^8He	^9He	^{10}He
		unbound	808 ms	unbound	119 ms	unbound	unbound

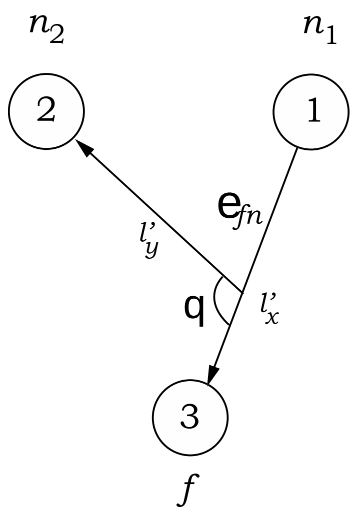


Johansson et al., Nucl. Phys. **A842** (2010) 15

$$\sqrt{2c^2} - \sqrt{2n - 1} = -1.56$$

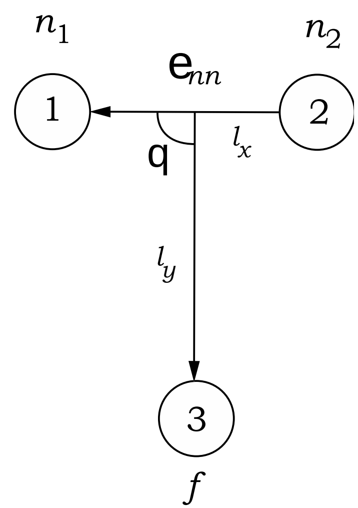
Neyman-Pearson test

^{8}He+n+n



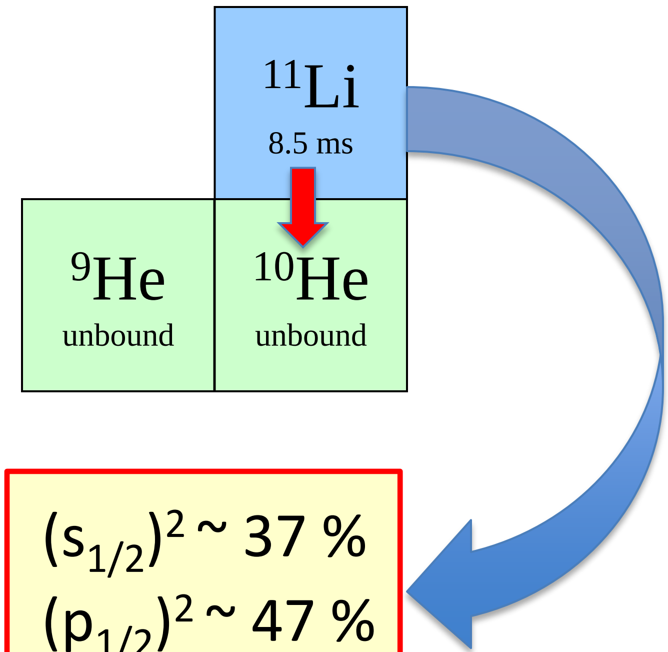
Y-system

$$\varepsilon_{fn} = E_{fn}/E$$



T-system

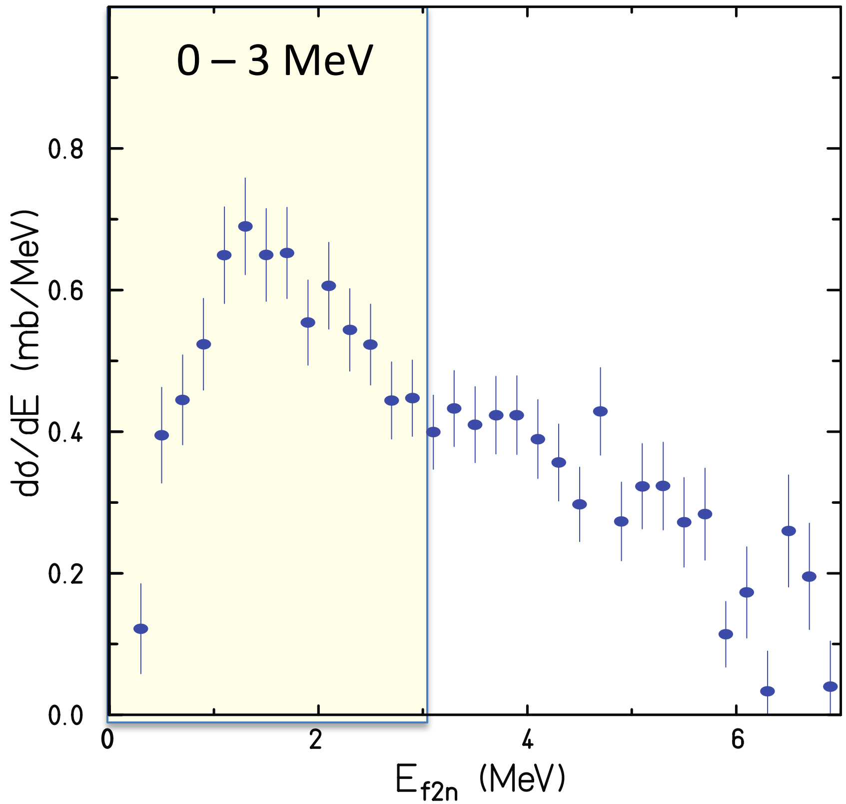
$$\varepsilon_{nn} = E_{nn}/E$$

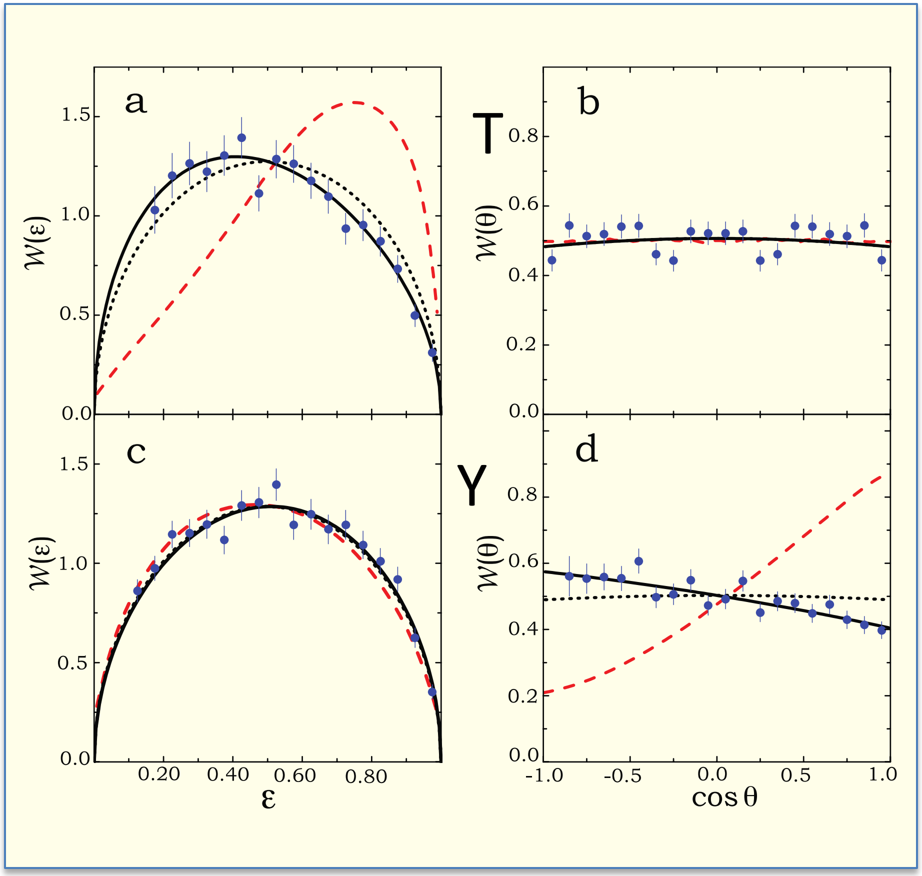


$(s_{1/2})^2 \sim 37\ \%$
$(p_{1/2})^2 \sim 47\ \%$
$(p_{3/2})^2 \sim\ 9\ \%$

N.B. Shulgina *et al.*, Nucl. Phys. **A825** (2009) 175

Energy and angular correlations

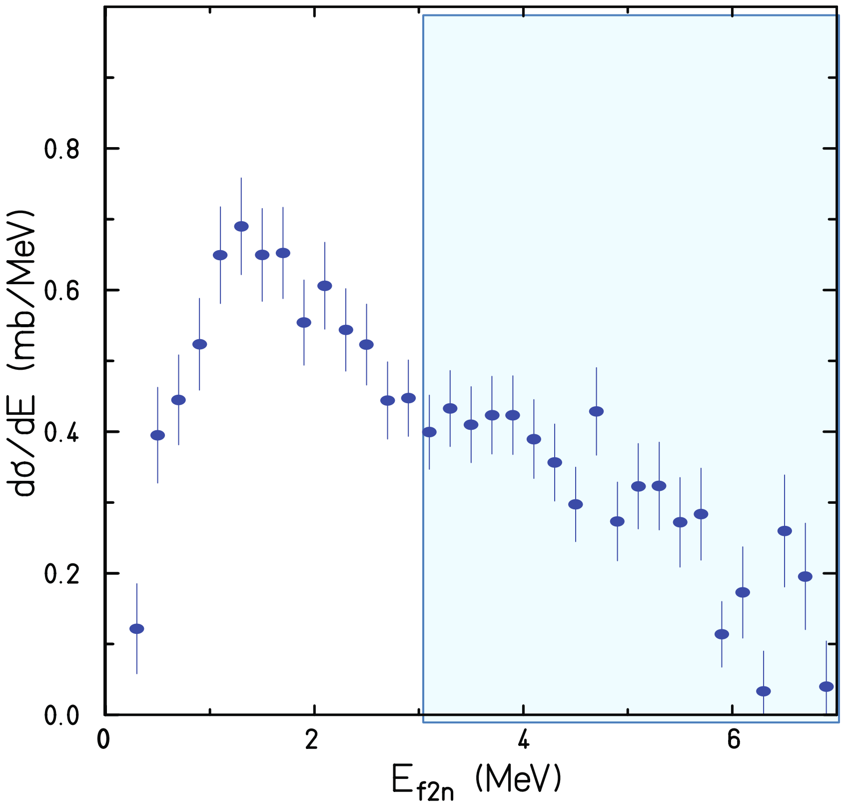


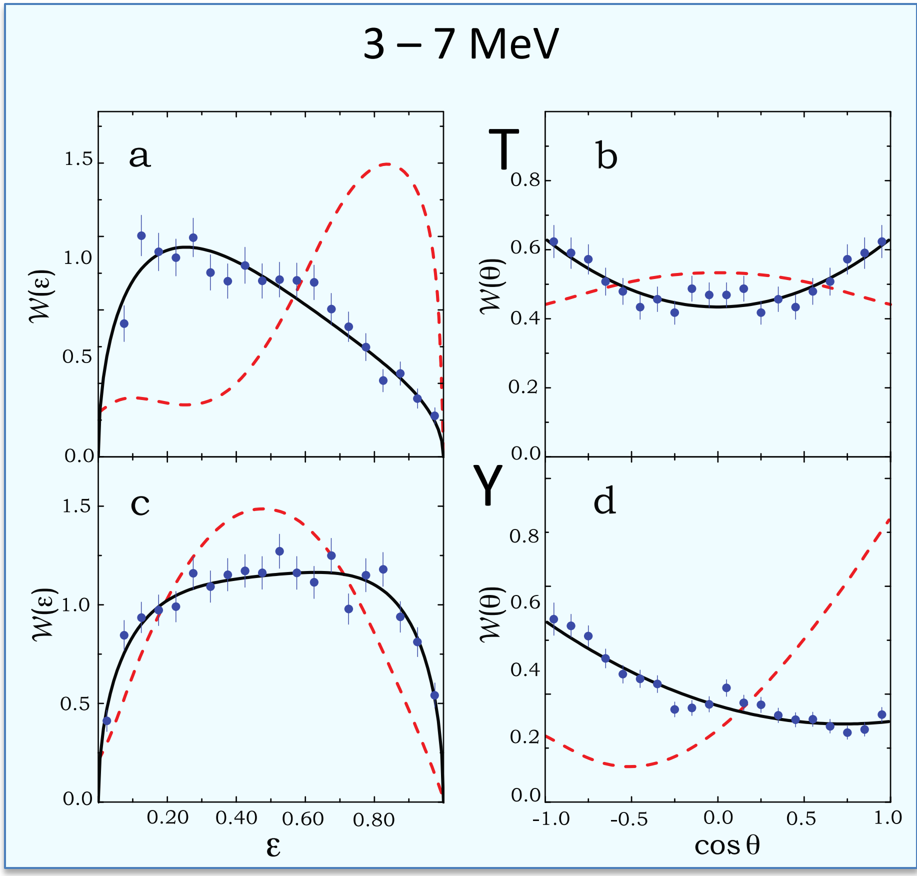


Restricted series of hyperspherical harmonics assuming $I^{\pi} = 0^{+}$ and $K \leq 2$

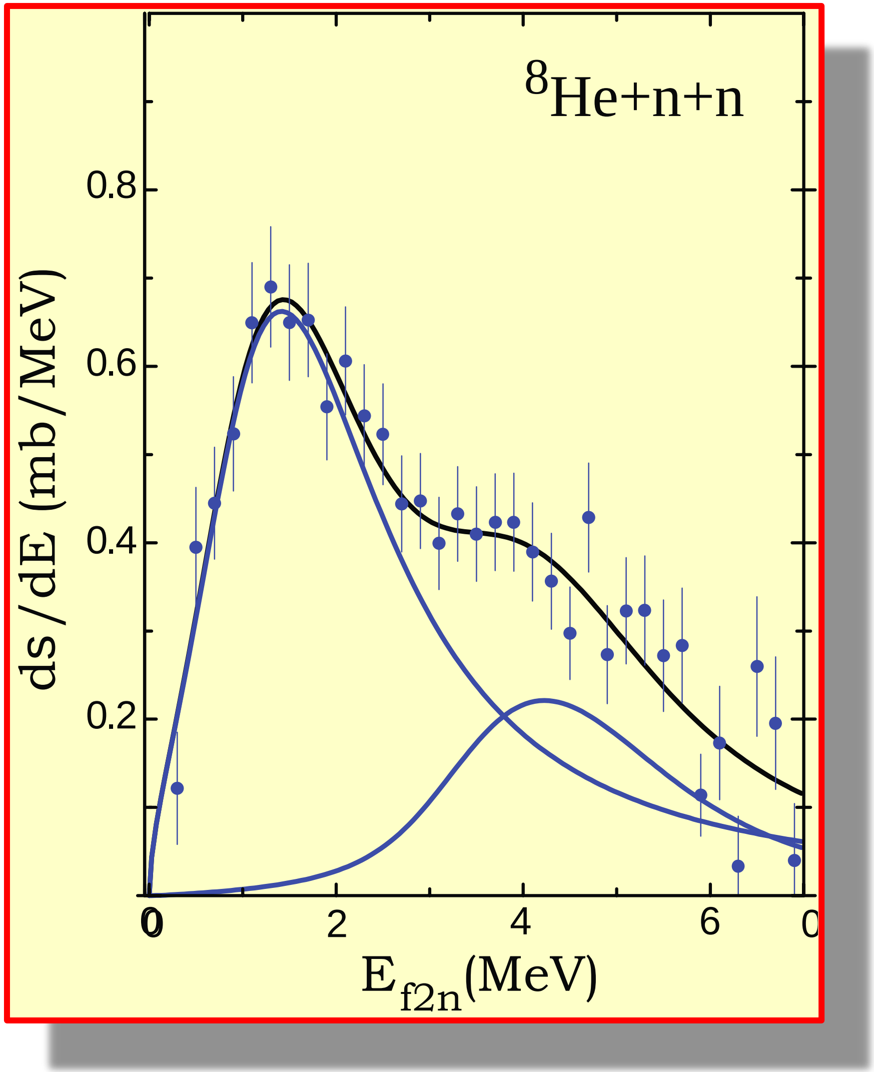
$$
\begin{aligned}
&\mathcal{W}_{0^+}(\varepsilon, \cos\theta) \\
&= \frac{4}{\pi}\sqrt{\varepsilon(1-\varepsilon)}\Big(|A^{000}_{00}|^2 + 4|A^{000}_{00}|\big[(1-2\varepsilon)|A^{200}_{00}|\cos\varphi^{200}_{00} \\
&\quad - 2\sqrt{2}\varepsilon(1-\varepsilon)\big(1-3\cos^2\theta\big)|A^{400}_{22}|\cos\varphi^{400}_{22}\big] + 4\big[(1-2\varepsilon)|A^{200}_{00}|^2 \\
&\quad - 4\sqrt{2}\varepsilon(1-\varepsilon)(3-2\varepsilon)\big(1-3\cos^2\theta\big)|A^{200}_{00}||A^{400}_{22}|\cos\big(\varphi^{200}_{00}-\varphi^{400}_{22}\big) \\
&\quad + 2\varepsilon(1-\varepsilon)\Big(\big(1-\cos^2\theta\big)|A^{211}_{11}|^2 + 4\varepsilon(1-\varepsilon)\big(1-3\cos^2\theta\big)^2|A^{400}_{22}|^2\Big)\big]\Big)
\end{aligned}
$$

Energy and angular correlations





Restricted series of hyperspherical harmonics assuming $I^{\pi} = 2^{+}$ and $K \leq 4$



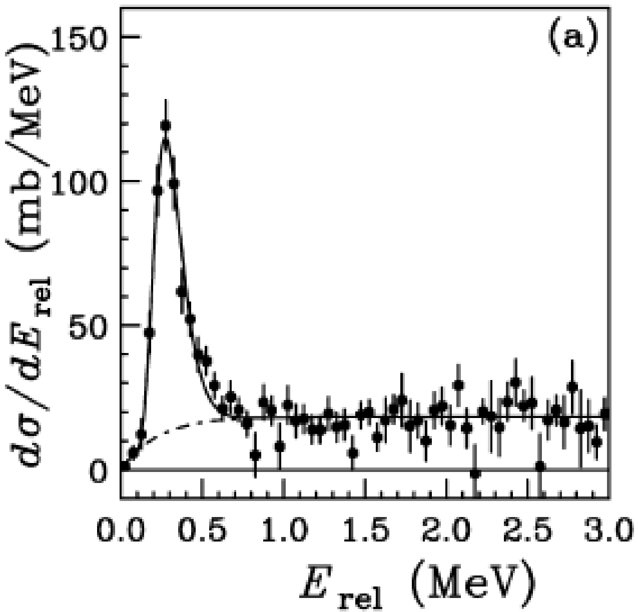
$^8He + n + n$

Ground state $I^p = 0^+$

Excited state $I^p = 2^+$

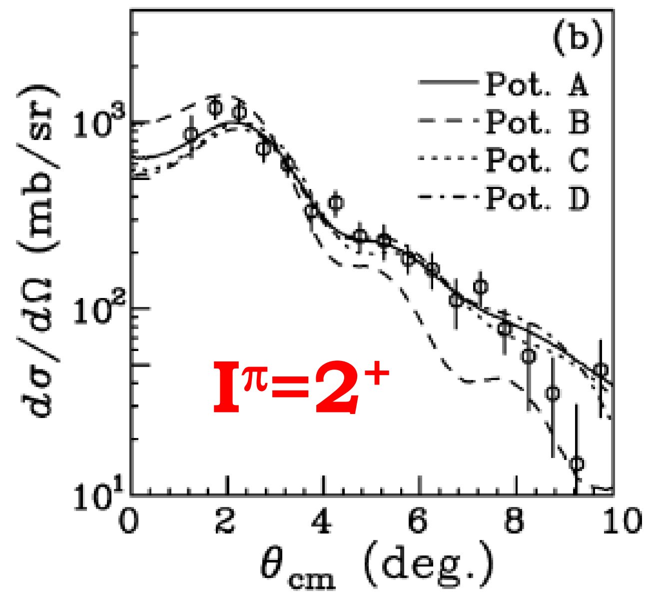
Johansson et al., Nucl. Phys. **A847** (2010) 66

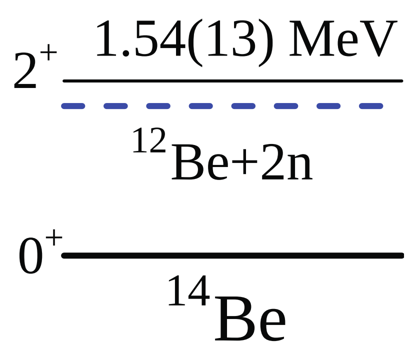
^{7}Be	^{8}Be	^{9}Be	^{10}Be	^{11}Be	^{12}Be	^{13}Be	^{14}Be	^{15}Be	^{16}Be
	unbound		1.6 10^{6} y	13.8 s	23.6 ms	unbound	4.35 ms	unbound	unbound

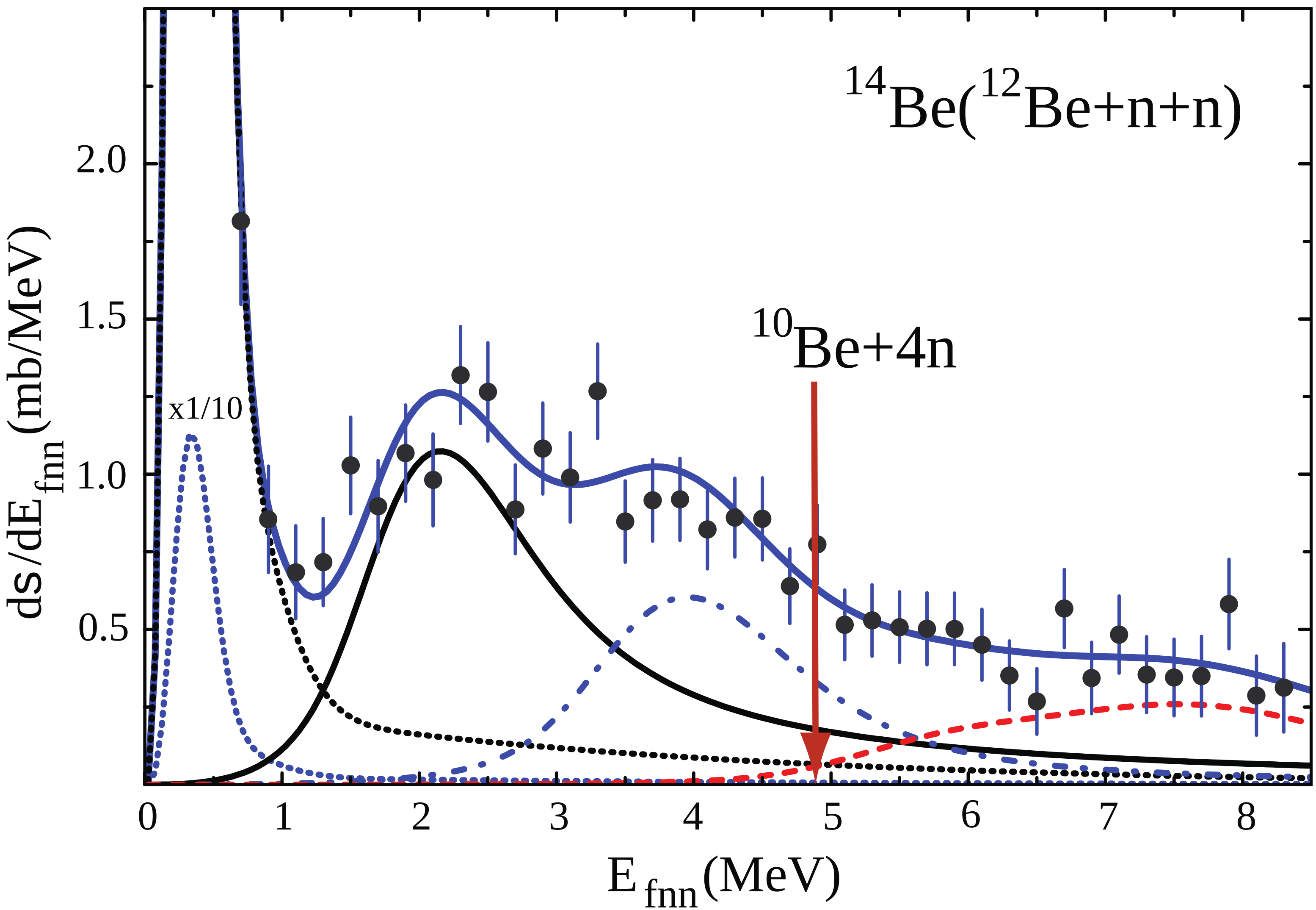


Sugimoto *et al.*,
Phys. Lett. **B654** (2007) 160

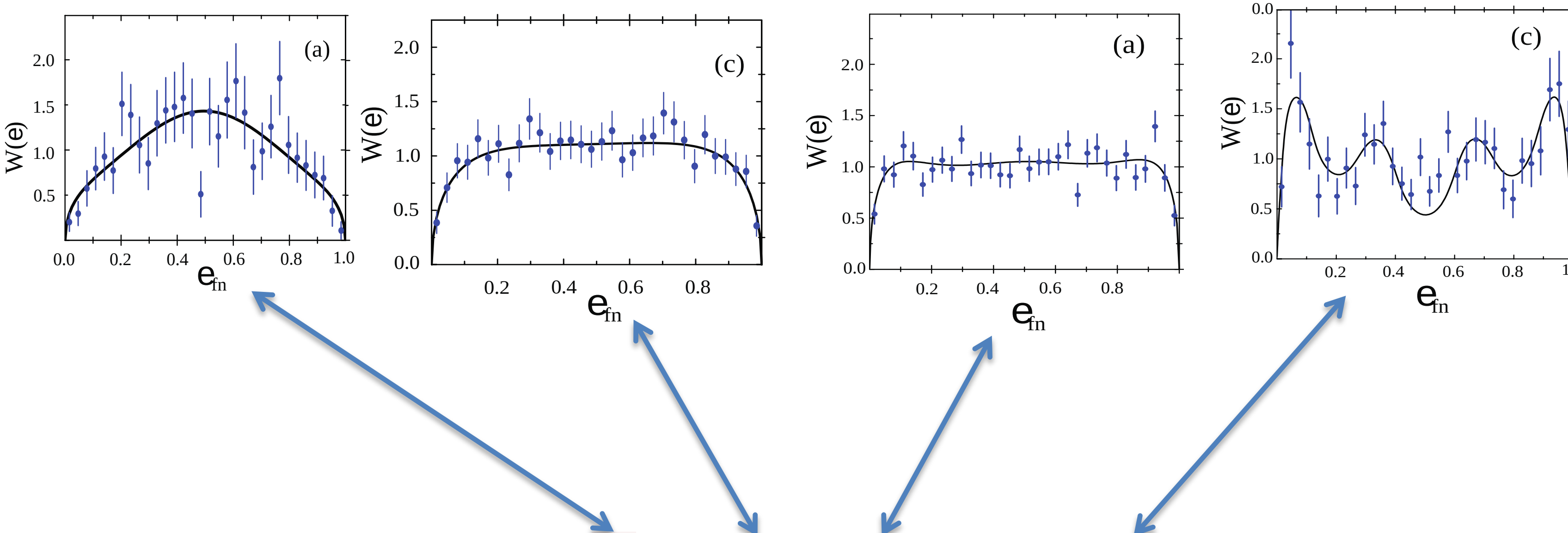
RIKEN
68 MeV/u ^{14}Be,
^{12}C target

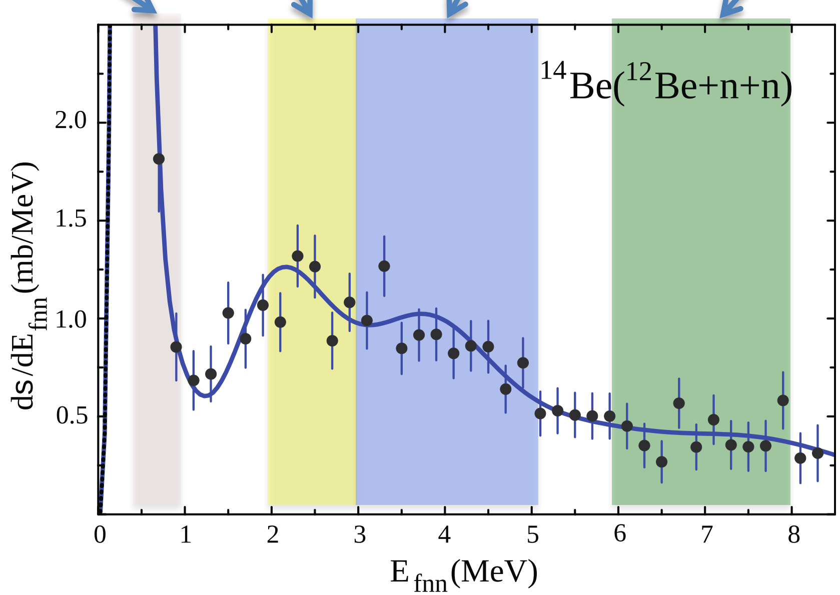






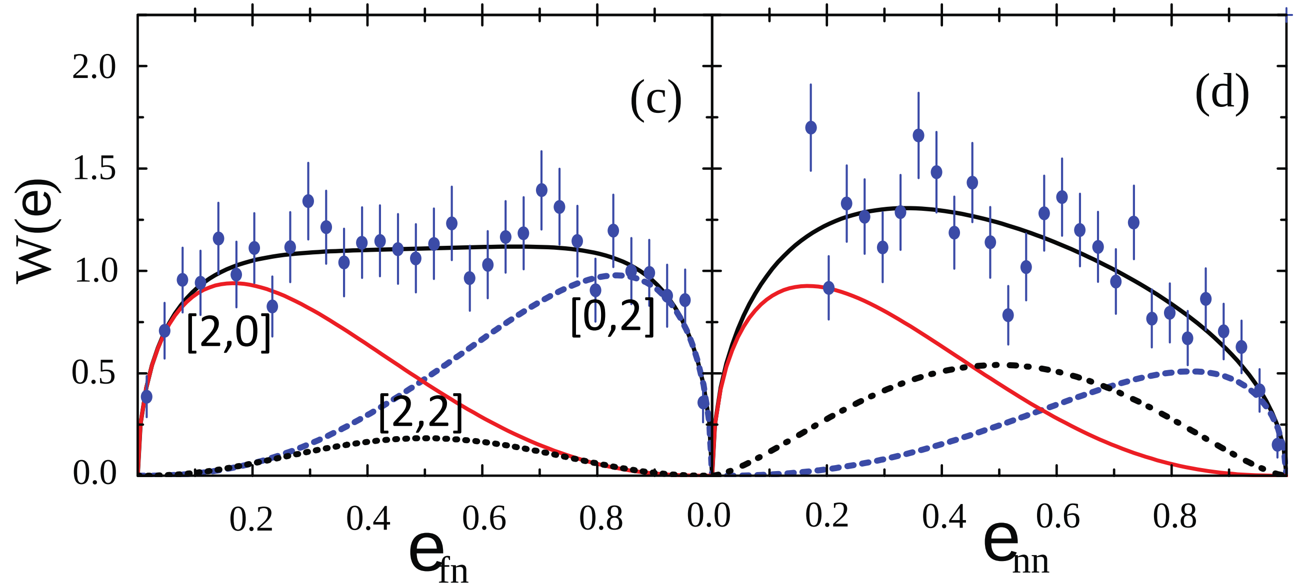
Yu. Aksyutina et al.,
PRL 111, 242501 (2013)





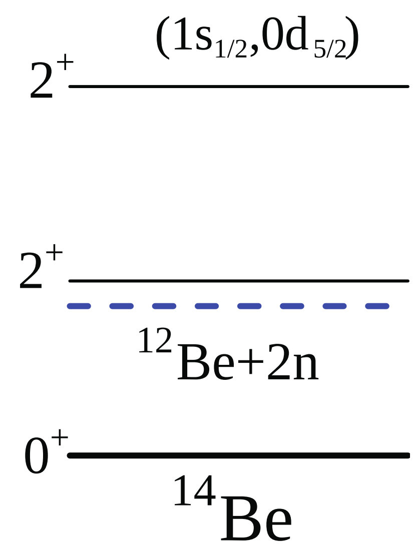
$$\varepsilon_{fn} = E_{fn}/E$$

2 MeV < E_{fnn} < 3 MeV



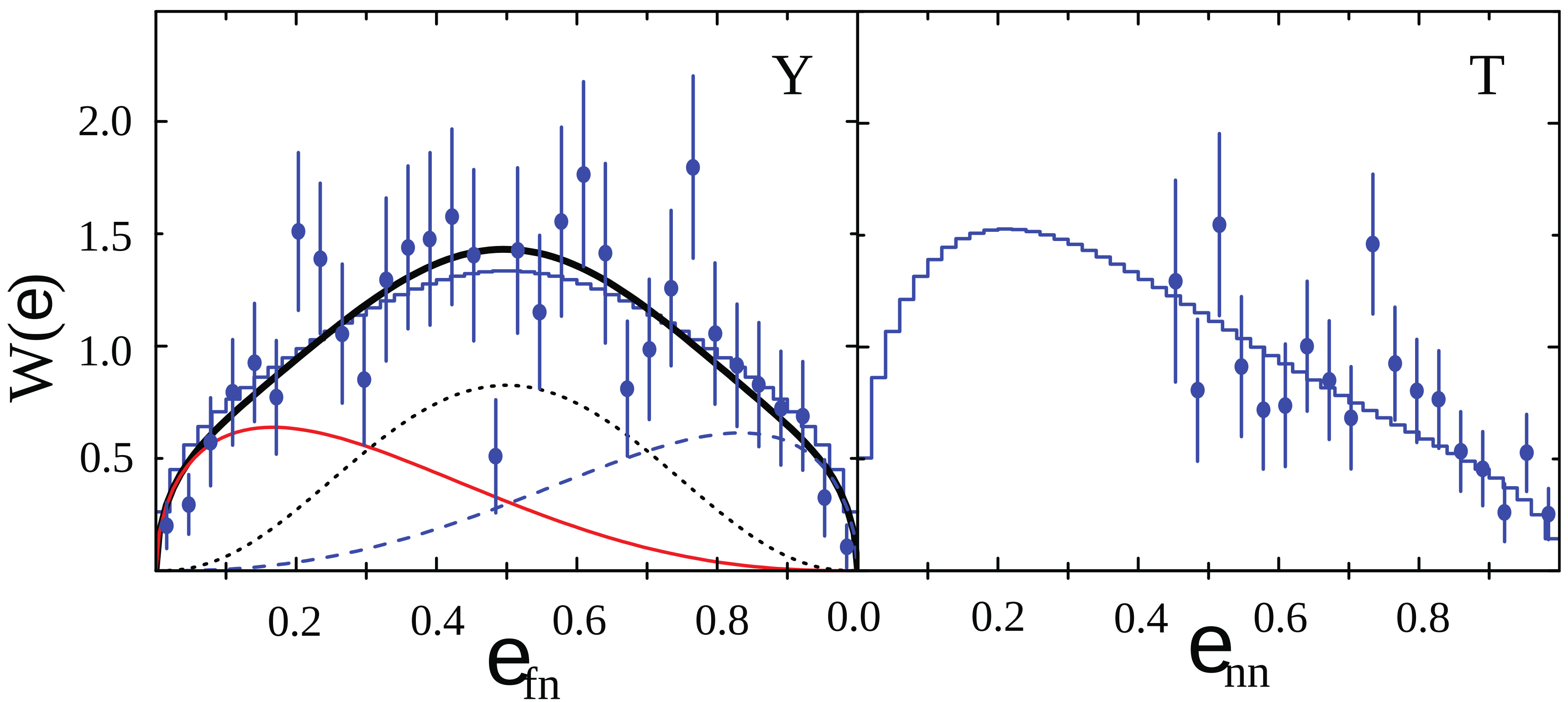
L.M. Delves, Nucl. Phys. **20** (1960) 275

$$W(\epsilon) \sim \sum_i A_i^2 \epsilon^{l_x^i + \frac{1}{2}} (1-\epsilon)^{l_y^i + \frac{1}{2}}$$



E* = 3.54(16) MeV, Γ = 1.5 MeV
$I^\pi = 2^+$
$(1s_{1/2}, 0d_{5/2}) \approx 90$ %

0.5 MeV < E_{fnn} < 1.0 MeV



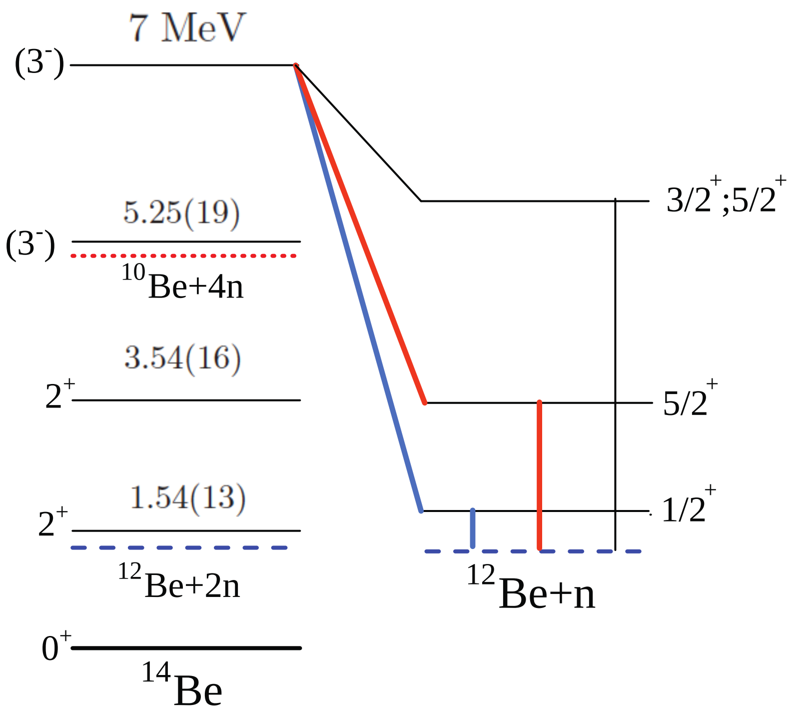
$$^{12}\mathrm{Be}(0^+) = ^{10}\mathrm{Be} \otimes \left[\alpha(1s_{1/2})^2_{I=0} + \beta(0p_{1/2})^2_{I=0} + \gamma(0d_{5/2})^2_{I=0} \right]$$

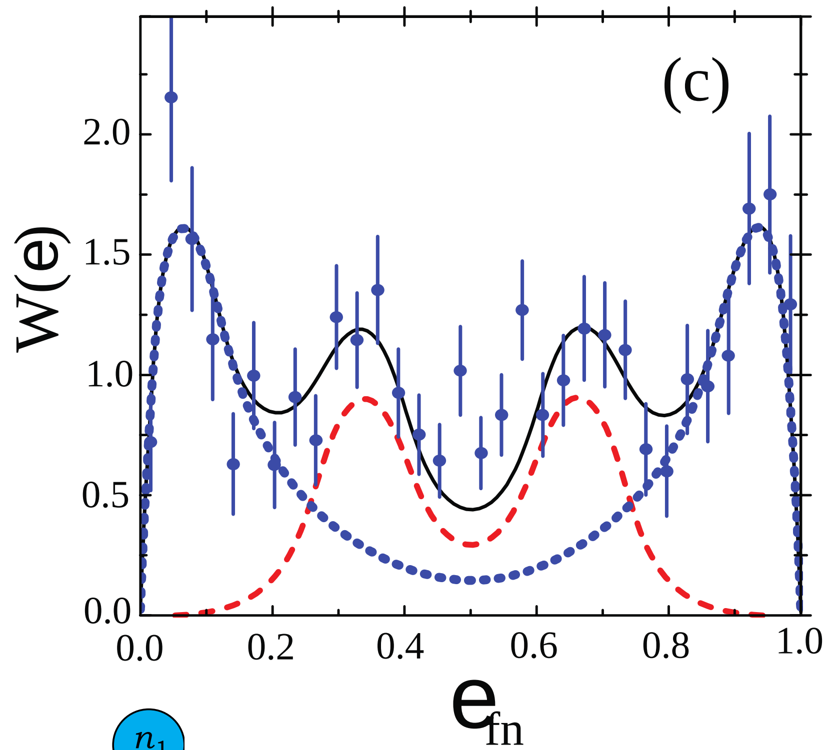
$$^{14}\mathrm{Be}(2^+) = ^{10}\mathrm{Be} \otimes \left[\left\{ \begin{array}{c} \alpha_1(1s_{1/2})^2_{I=0} \\ \alpha_2(0p_{1/2})^2_{I=0} \\ \alpha_3(0d_{5/2})^2_{I=0} \end{array} \right\} (0d_{5/2})^2_{I=2} + \left\{ \begin{array}{c} \beta_1(0p_{1/2})^2_{I=0} \\ \beta_2(0d_{5/2})^2_{I=0} \end{array} \right\} (1s_{1/2}, 0d_{5/2})_{I=2} \right]$$

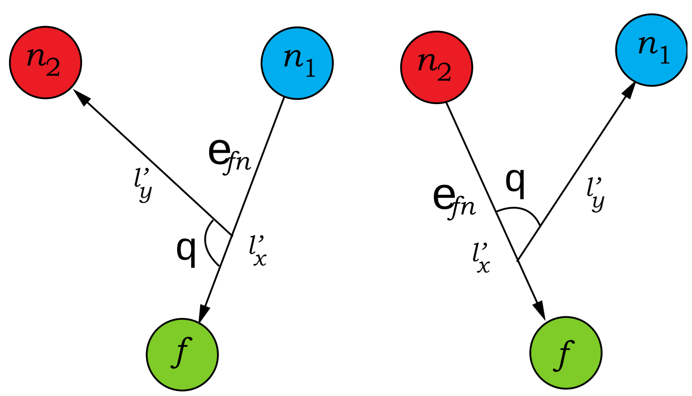
$$\alpha_1\alpha + \alpha_2\beta + \alpha_3\gamma \quad l = 2$$

$$\beta_1\beta + \beta_2\gamma \qquad l = 0, 2$$

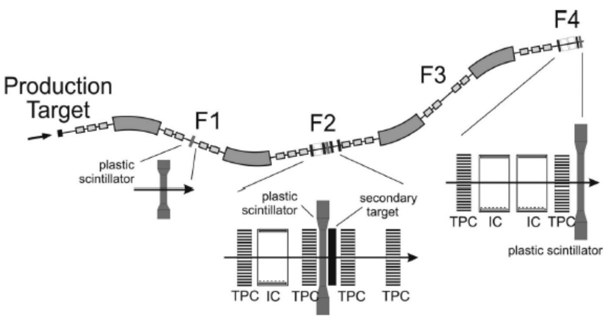
Sequential Decay

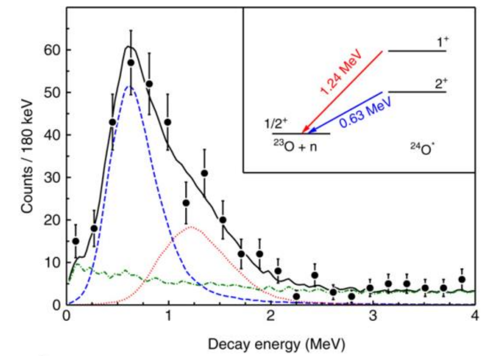






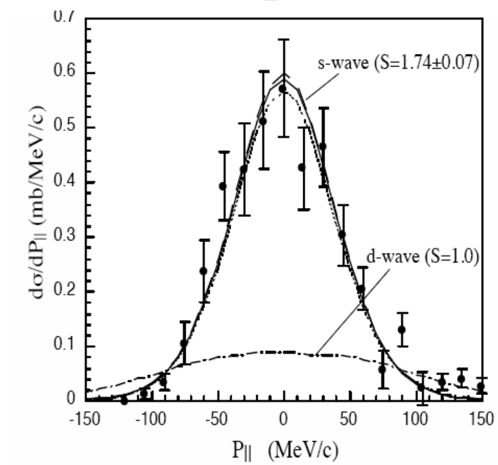
^{20}F 11 s	^{21}F 4.16 s	^{22}F 4.236 s	^{23}F 2.23 s	^{24}F 0.34 s	^{25}F 50 ms	^{26}F 10.2 ms	^{27}F 4.29 ms		^{29}F 2.6 ms		^{31}F >260 ns
^{19}O 27.1 s	^{20}O 13.5 s	^{21}O 3.4 s	^{22}O 2.25 s	^{23}O 82 ms	^{24}O 61 ms				^{28}O unbound		
^{18}N 0.63 s	^{19}N 329 ms	^{20}N 142 ms	^{21}N 95 ms	^{22}N 24 ms	^{23}N 14.5 ms						
^{17}C 193 ms	^{18}C 92 ms	^{19}C 49 ms	^{20}C 14 ms		^{22}C 6.2 ms						



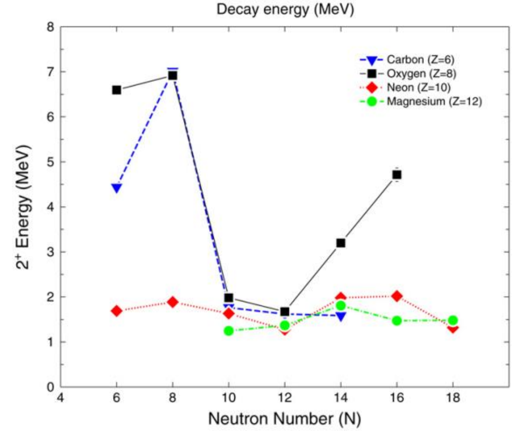


MSU

GSI



S=1.74(19)



2^+: 4.7 MeV

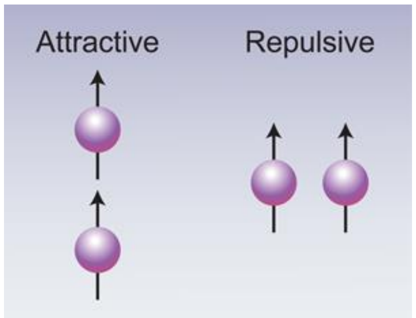
C.R. Hoffman et al.,
PLB **672** (2009) 17

R. Kanungo *et al.*, PRL **102** (2009) 152501

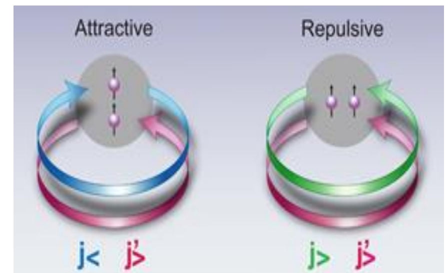
Shell evolution and nuclear forces

N.A. Smirnova *et al.*, PLB **686** (2010) 109

Novel Features of Nuclear Forces and Shell Evolution in Exotic Nuclei

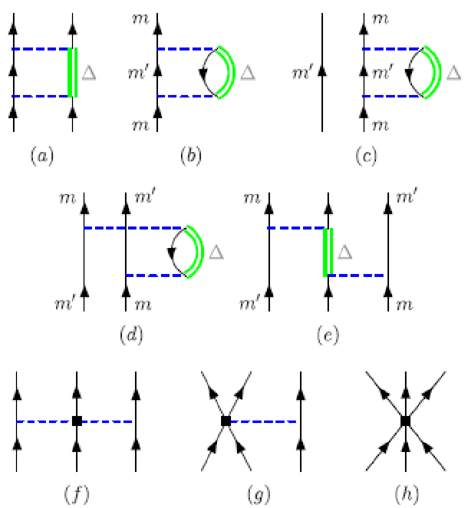


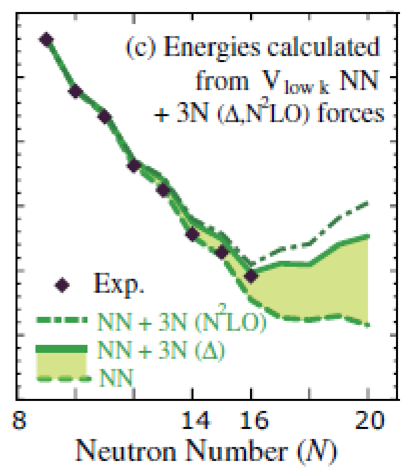
T. Otsuka *et al.*, PRL **104** (2010) 032501

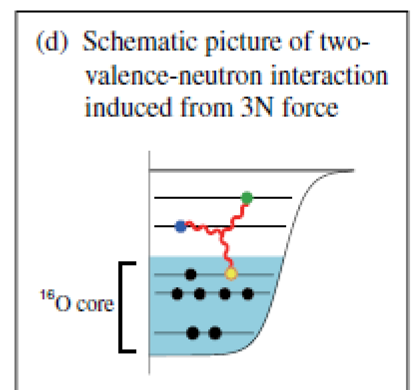


Three-Body Forces and the Limit of Oxygen Isotopes

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



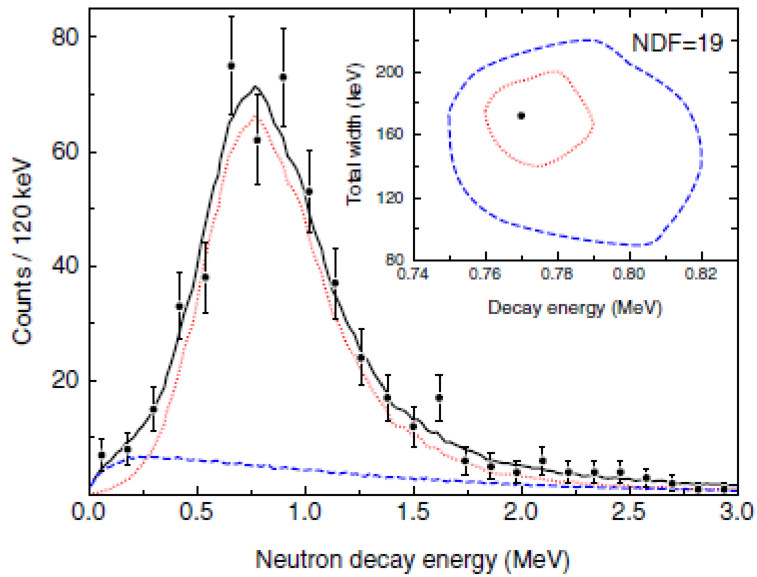




GSI : Data September 2010

^{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	^{30}F unbound	^{31}F >260 ns
^{23}O 82 ms	^{24}O 61 ms	^{25}O unbound	^{26}O unbound		^{28}O unbound		

MoNA



E_{decay}=770 keV,
Γ= 172 keV, l=2

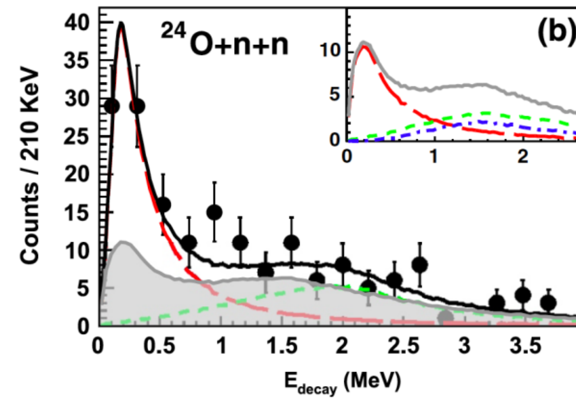
Shell gap $\nu 1s_{1/2} - \nu 0d_{3/2}$
4.86(13) MeV

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

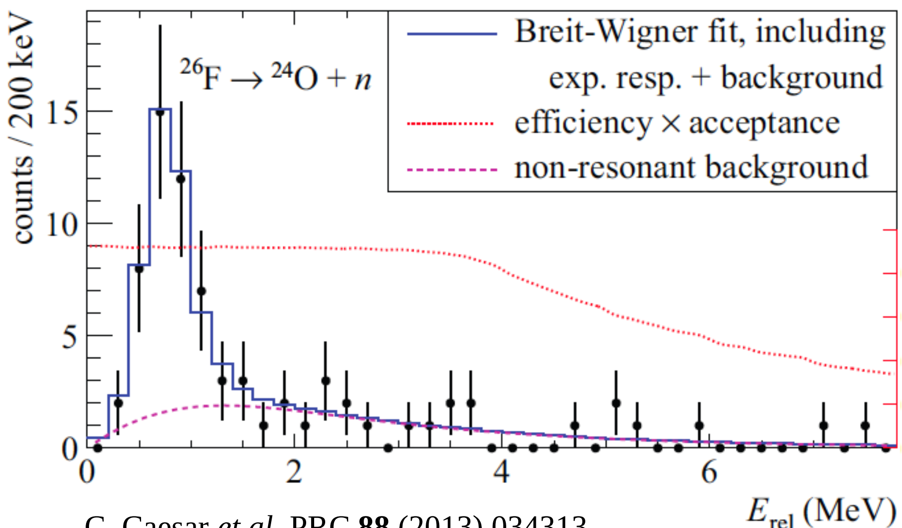
B. Jurado*et al*. PLB **649** (2007) 43

GSI : Data September 2010

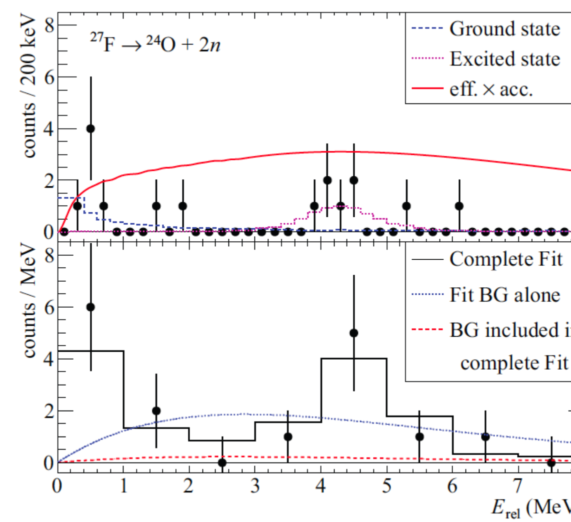
^{24}F 0.34 s	^{25}F 50 ms	^{26}F 10.2 ms	^{27}F 4.9 ms	^{28}F unbound	^{29}F 2.6 ms	^{30}F unbound	^{31}F >260 ns
^{23}O 82 ms	^{24}O 61 ms	^{25}O unbound	^{26}O unbound		^{28}O unbound		



E. Lunderberg *et al*. PRL **108** (2012) 142503



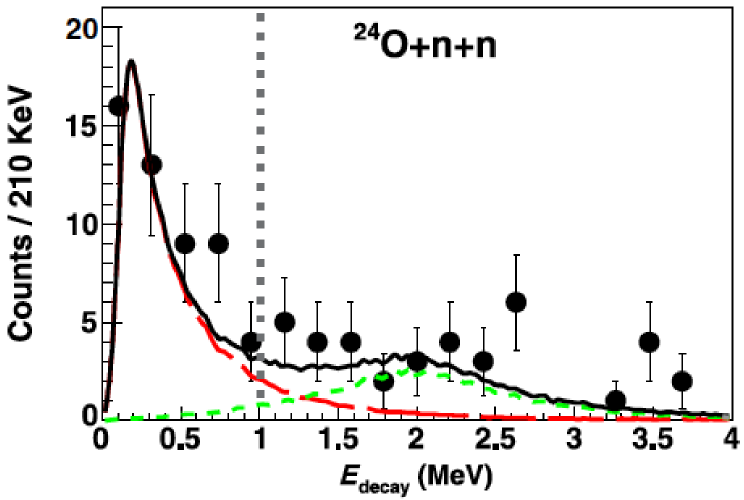
C. Caesar *et al*. PRC **88** (2013) 034313

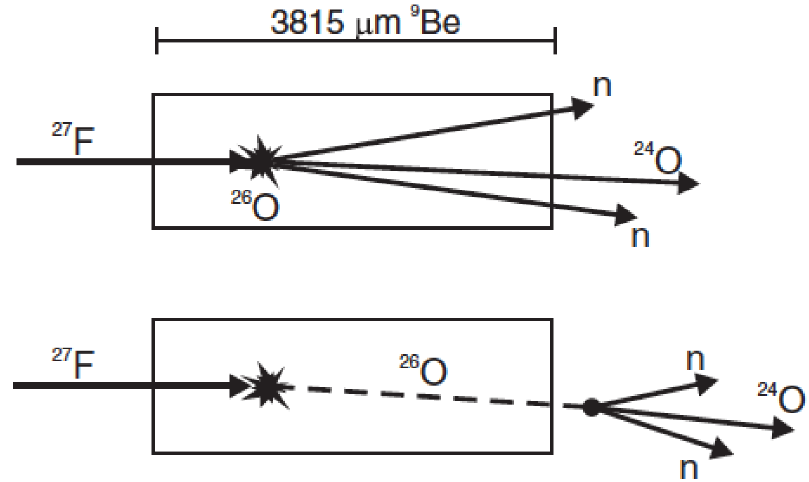


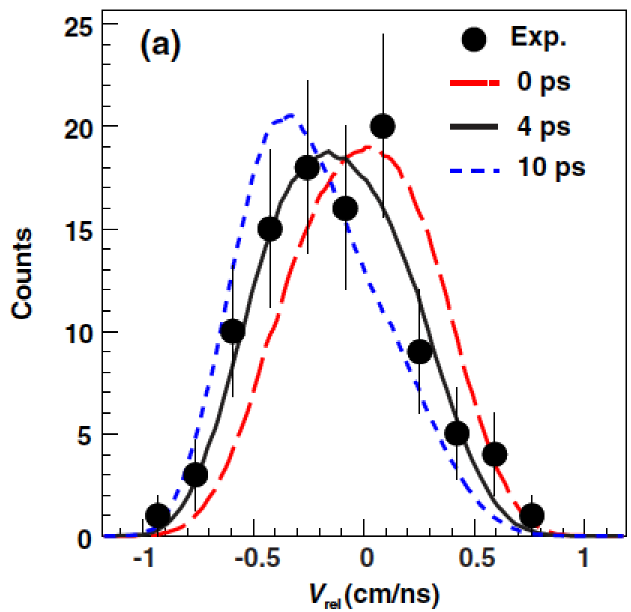
Two-neutron radioactivity ?

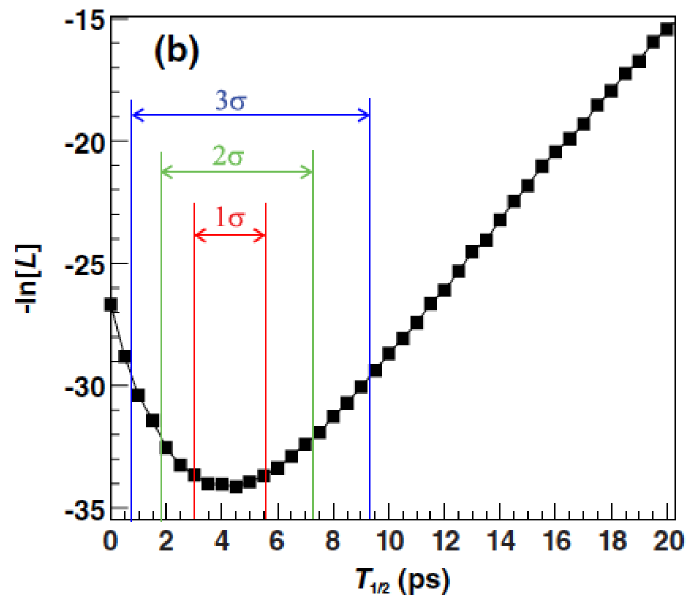
L.V. Grigorenko *et al*. PRL **111** (2013) 042501

Z. Kohley *et al*. PRL **110** (2013) 152501 ← $4.5^{+1.1}_{-1.5} \pm 3\ ps$









Negative log-likelihood
(-ln[L])

Z. Kohley *et al*. PRL **110** (2013) 152501

$$4.5^{+1.1}_{-1.5} \pm 3\ ps$$

To view the world in this way
Is to see it with the eyes of a gambler.
Our best choice is to cast the die again and again.
To let it keep rolling in the hope
That it will give returns high enough
to inspire new expectations.

Att betrakta världen så är att se
på den med tärningsögon.
Vårt bästa val är att kasta tärningen ofta, ofta.
Att ständigt låta den rulla, att den må falla ut
med en kvot stor nog
för en ny förväntan att andas.

Harry Martinson
Tärningspelet, 1971