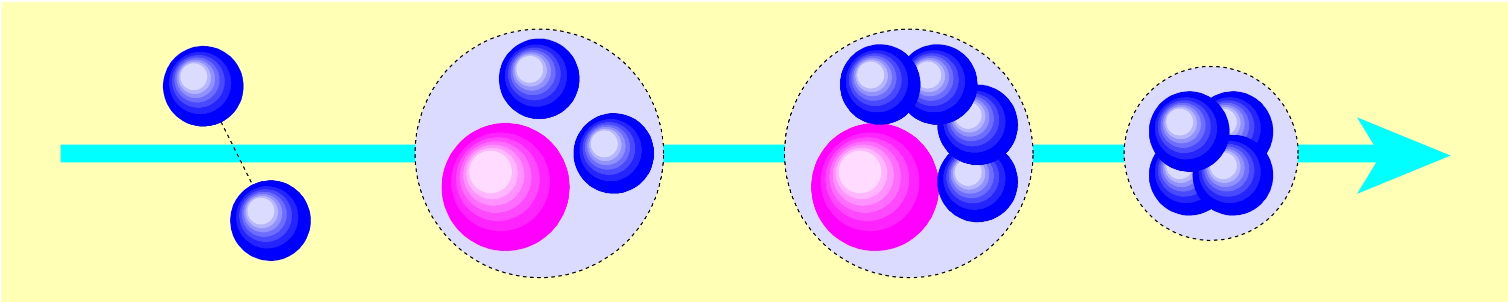
HALO 06 .com
Workshop: The Physics of Halo Nuclei
(ECT*, Trento, Italy)

Probing Correlations in Many-Neutron Systems



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⋆ E295/E378: LPC-Caen [N.A. Orr, M. Labiche, G. Normand], Surrey, Oxford, Birmingham, ULB-Bruxelles [V. Bouchat], IReS-Strasbourg, GANIL, Orsay, Göteborg, Aarhus, Madrid

the n-n interaction

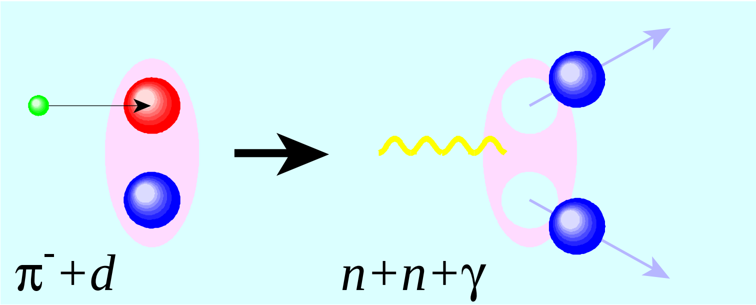
▶ low energy N-N interaction :

$$f_s(k) = \frac{e^{i\delta(k)}}{k} \sin\delta(k)$$

$$\sigma_s(E) = \frac{4\pi}{k^2} \sin^2\delta \overset{k \to 0}{=} 4\pi\, a_0{}^2$$

$$k \cot\delta = \frac{-1}{a_0} + 1/2\, d_0\, k^2 + \cdots \quad \left[\frac{-1}{a(k)}\right]$$

▶ neutron-neutron "collisions" ?



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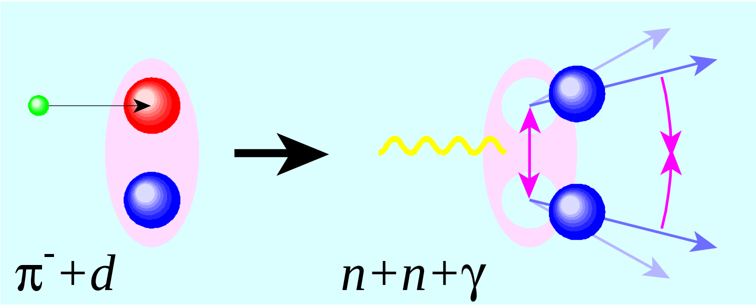


▷ final state modified by V_{nn} !

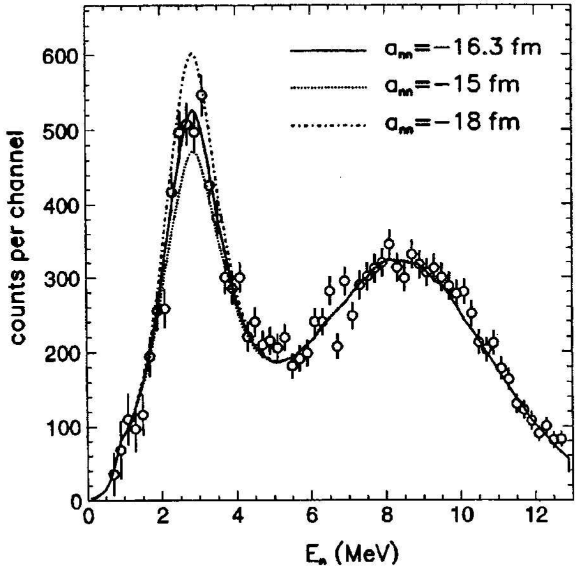
▶ how is it modified ?

▷ by the n-n distance

▷ by the n-n interaction

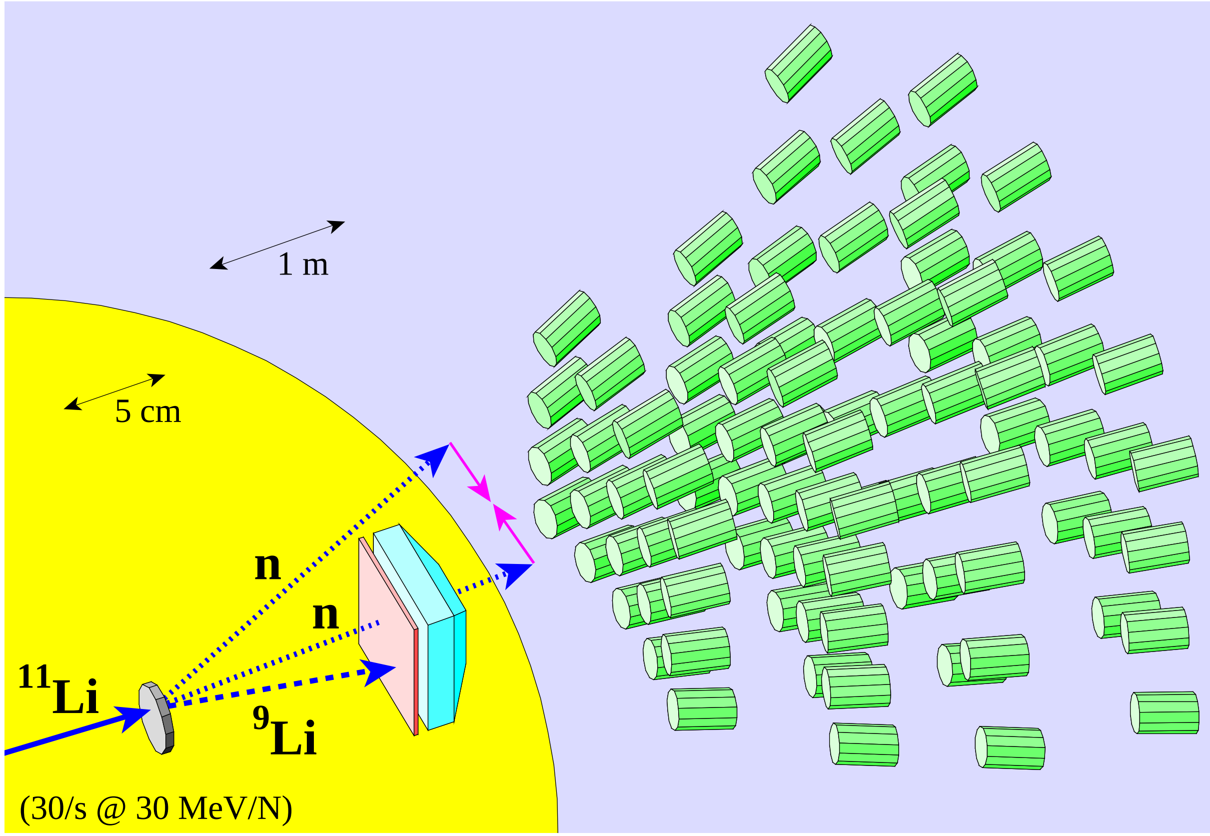
$$\sigma(q) \approx \Omega(q) \times \left| \int \psi_d\, \psi_s^*(a_{nn})\, d^3r \right|^2$$

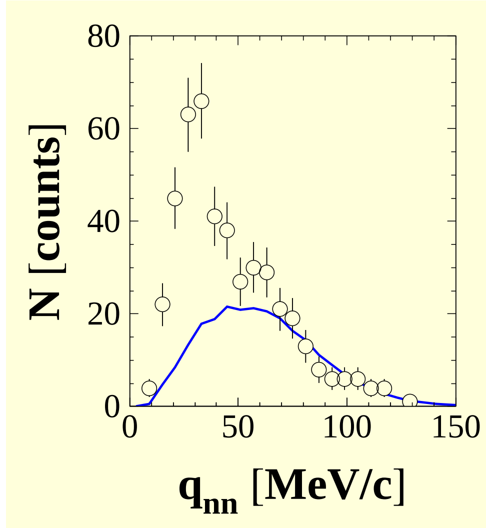
$$\approx \Omega(q) \times \frac{1}{1 + q^2\, a_{nn}{}^2}$$



the n-n configuration : interferometry

▸ the halo of ^{11}Li : ? ↔ ?



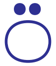


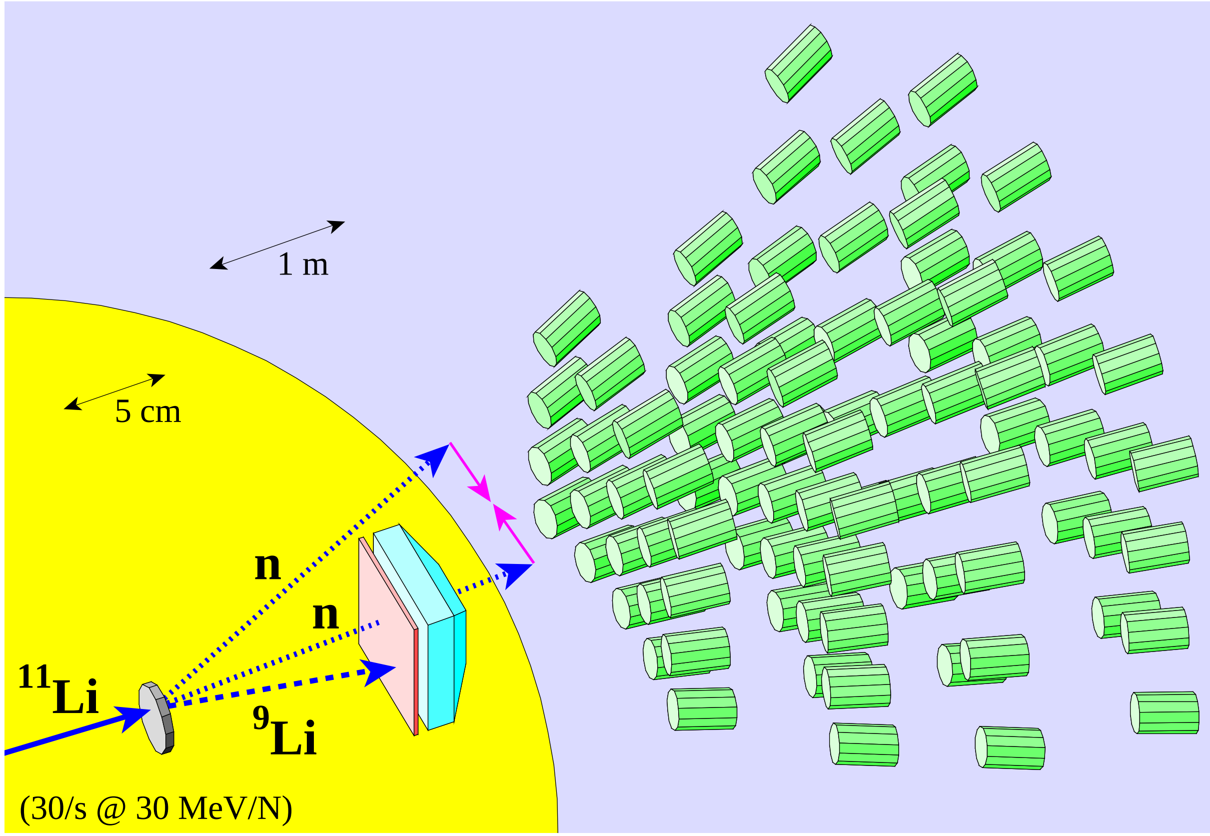
▹ $\sigma(q) \equiv \Omega(q) \times C_{nn}\,\{\psi(r_{nn}), a_{nn}\}$:

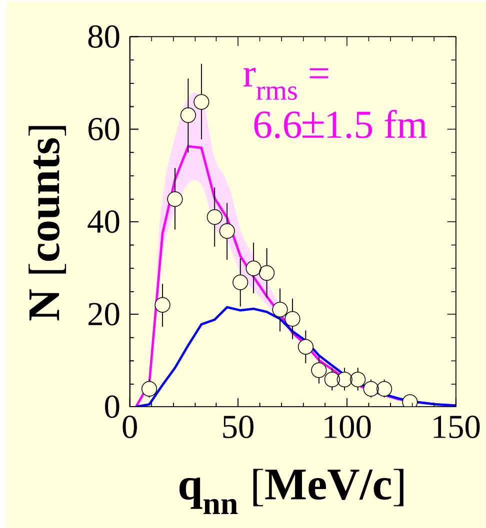
⇝ $\sigma(q)$ is measured

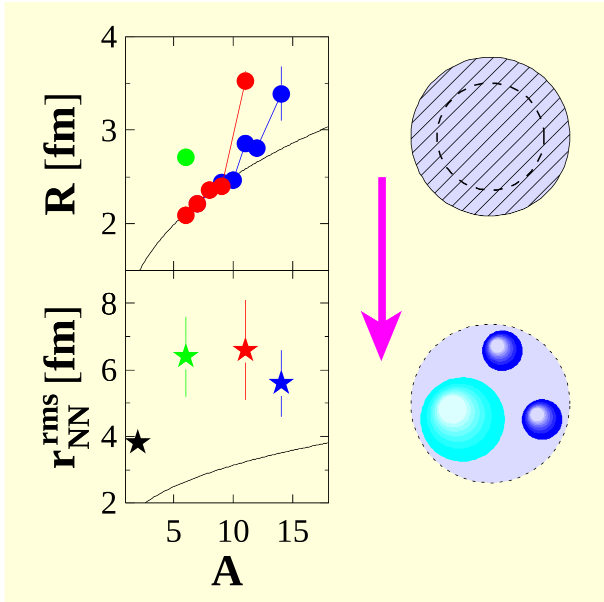
⇝ event mixing provides $\Omega(q)$ …

the n-n configuration : interferometry

▶ the halo of ^{11}Li :  ↔  ?







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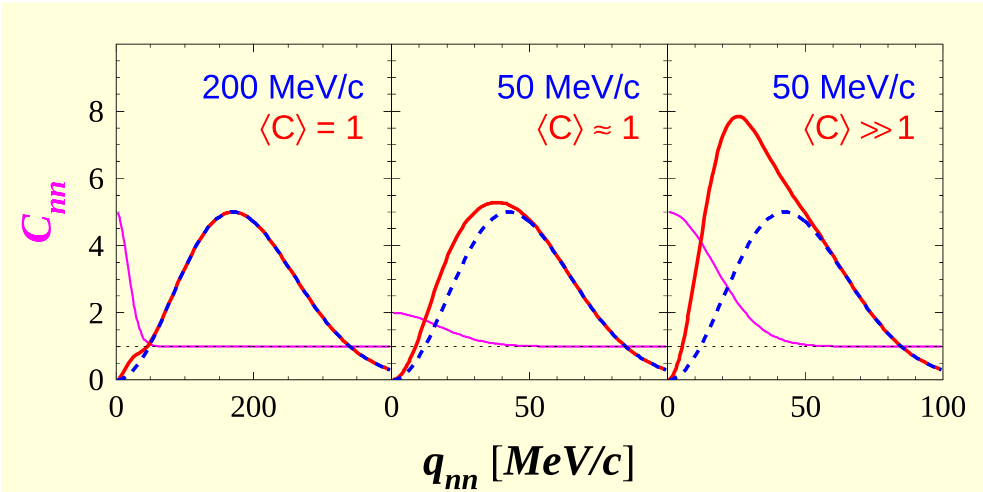
event mixing : residual correlations !

$$C(p_1,p_2) = \frac{d^2\sigma/dp_1dp_2}{(d\sigma/dp_1)\,(d\sigma/dp_2)}$$

▷ mixing events provides :

$$\frac{d\tilde{\sigma}}{dp} = \int \frac{d^2\sigma}{dp\,dk}\,dk = \frac{d\sigma}{dp}\int C(p,k)\,\frac{d\sigma}{dk}\,dk = \frac{d\sigma}{dp}\,\langle C\rangle(p)$$



▷ if this effect is ignored :

$$\frac{d^2\sigma/dp_1dp_2}{(d\tilde{\sigma}/dp_1)\,(d\tilde{\sigma}/dp_2)} < C$$

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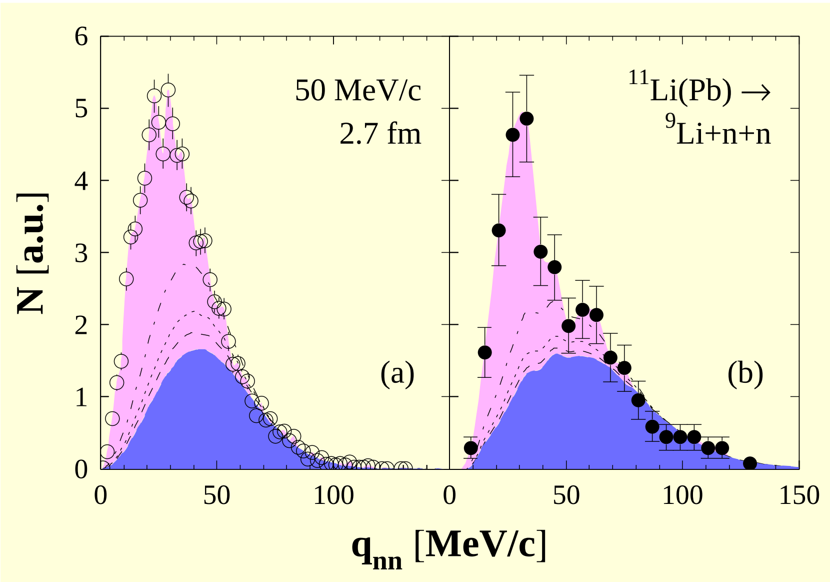

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$$\frac{d^2\sigma/dp_1dp_2}{(d\tilde{\sigma}/dp_1)\,(d\tilde{\sigma}/dp_2)} < C$$

▶ SOLUTION :

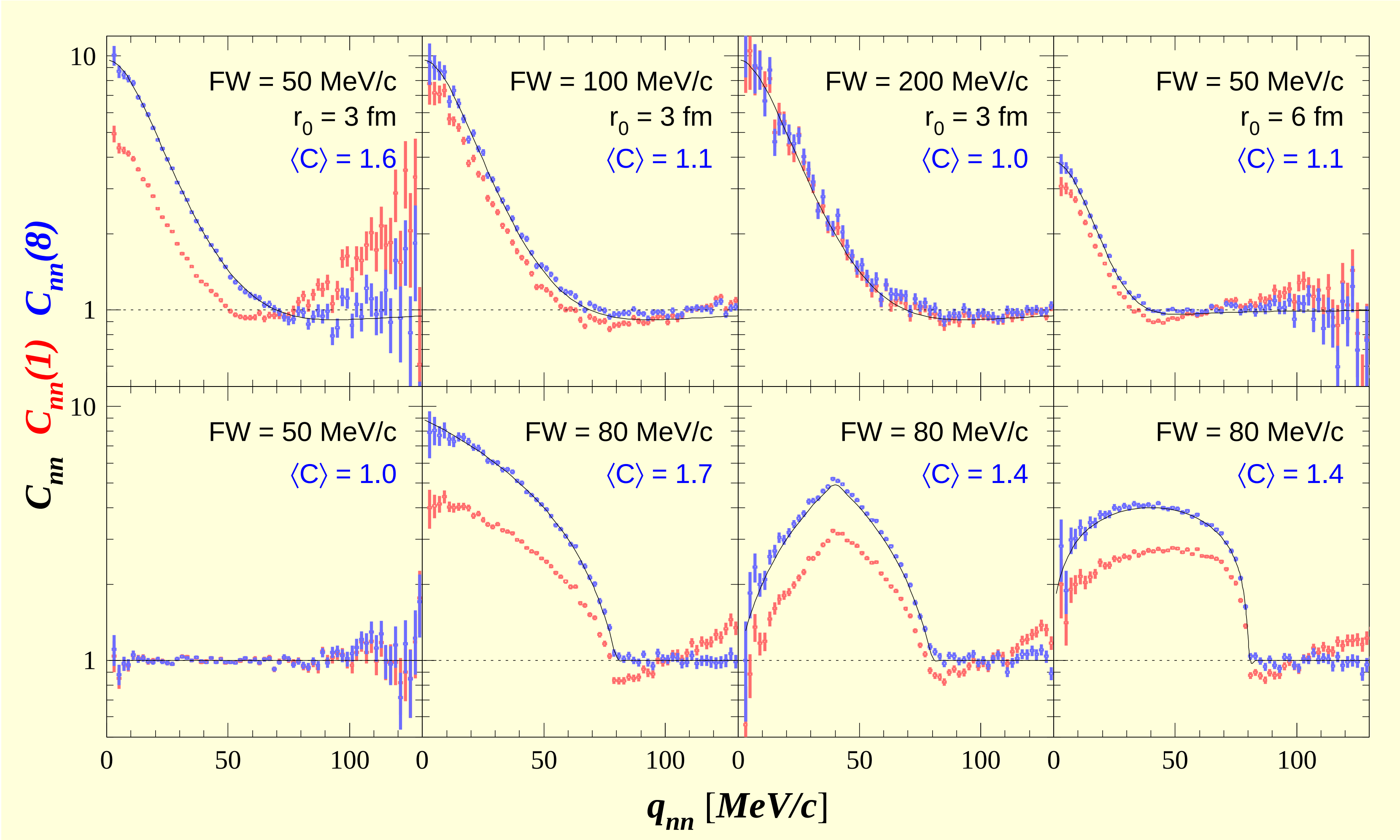
▷ assign to each neutron
a weight in the mixing given by :

$$w(p_i) = 1/\langle C\rangle(p_i)$$

▷ C is needed in order to build C …

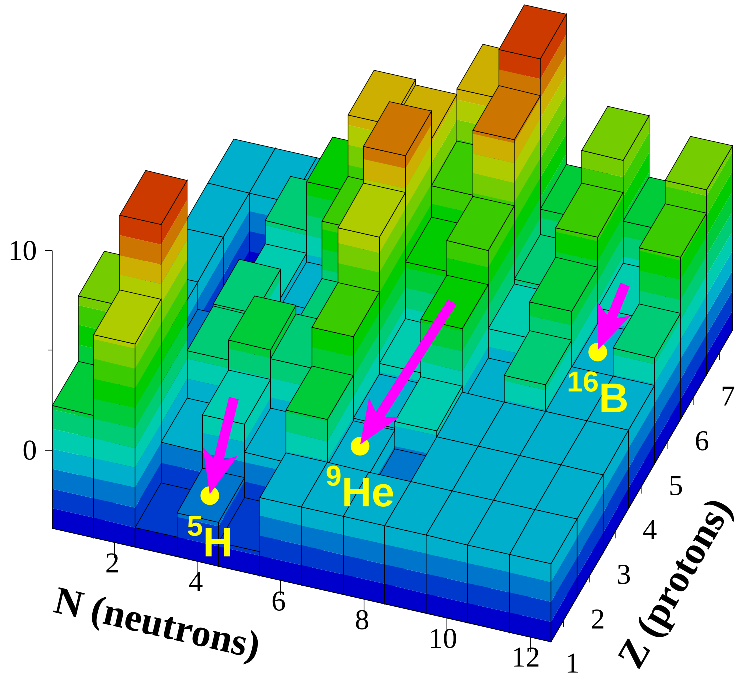
$$w^{(1)}=1 \;\rightarrow\; M^{(1)} \rightarrow C^{(1)}$$
$$\rightarrow w^{(2)} \;\rightarrow\; M^{(2)} \rightarrow C^{(2)}$$
$$\rightarrow w^{(3)} \;\rightarrow\; \cdots \rightarrow C \;!!!$$

how does it work ?

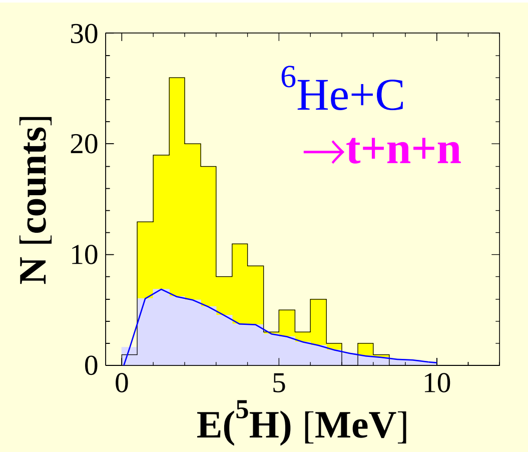


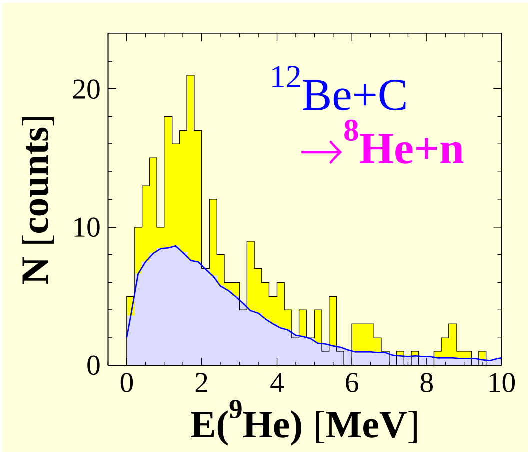
▷ recover input C_{nn} of unknown shape !!!

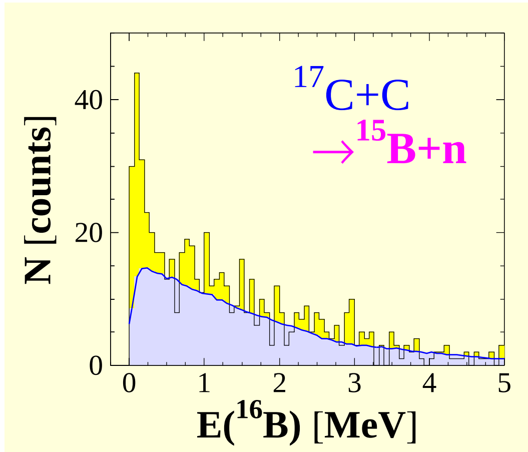
unbound nuclei



- ▶ how to look for them ?
  - ▷ strip nucleons from a beam !
- ▶ how to find them ?
  - ▷ look for energy levels …

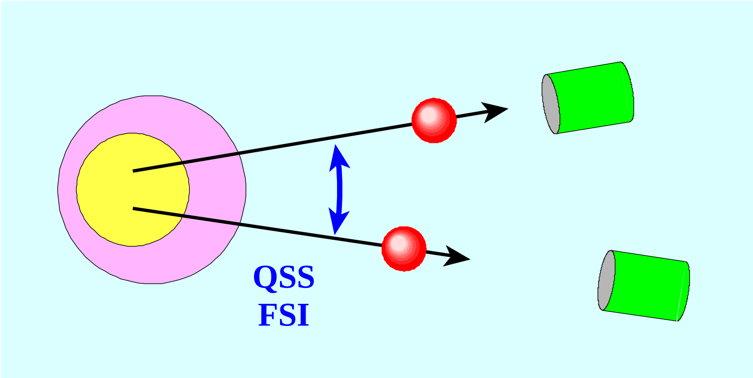


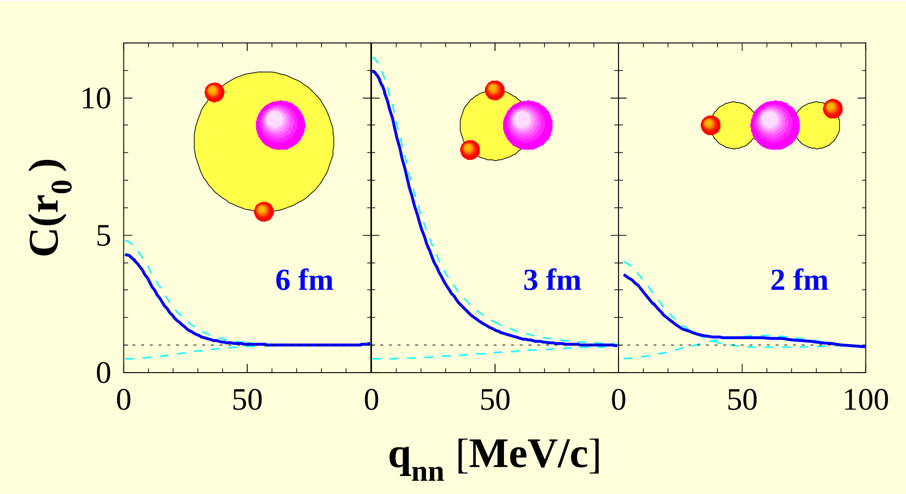




results on Pb and C targets

▶ Ψ_{2n} modified by relative distance :





[Lednicky & Lyuboshits, SJNP 35 (1982) 770]

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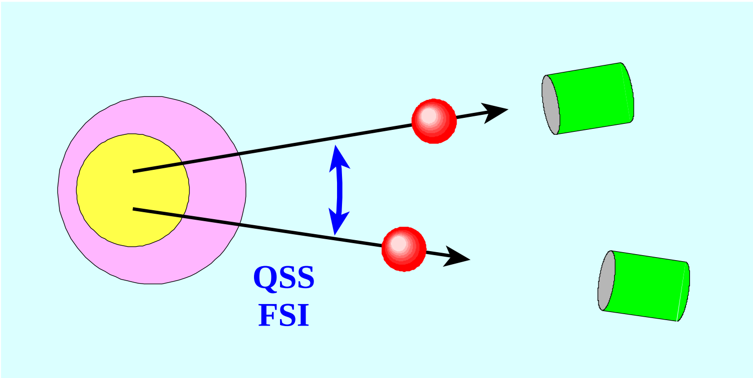

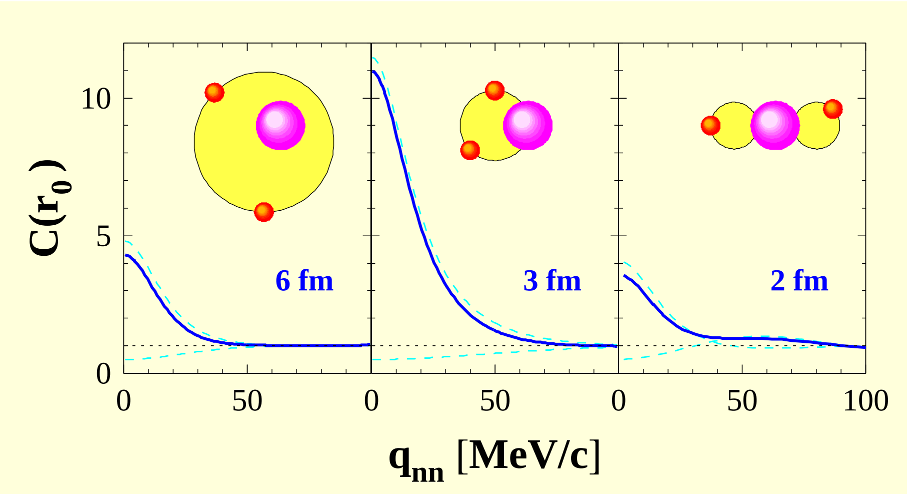

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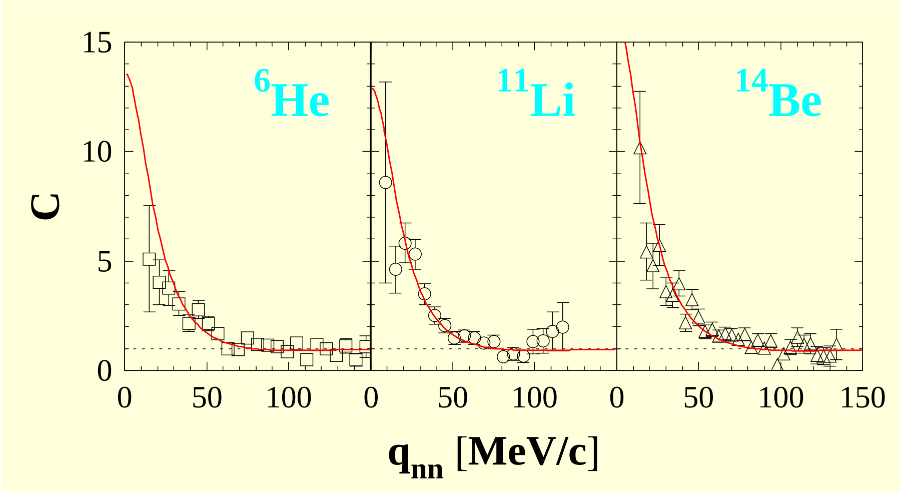

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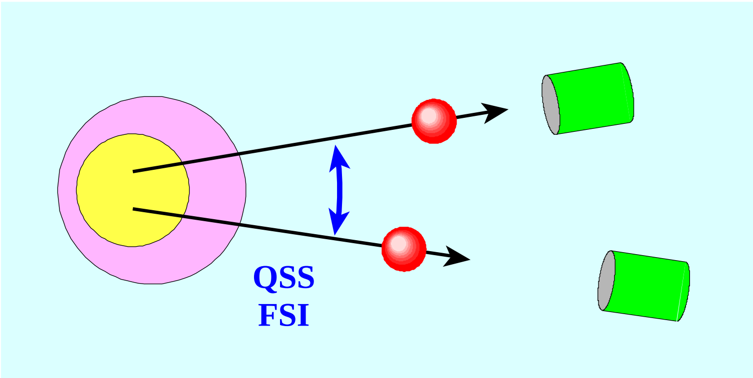

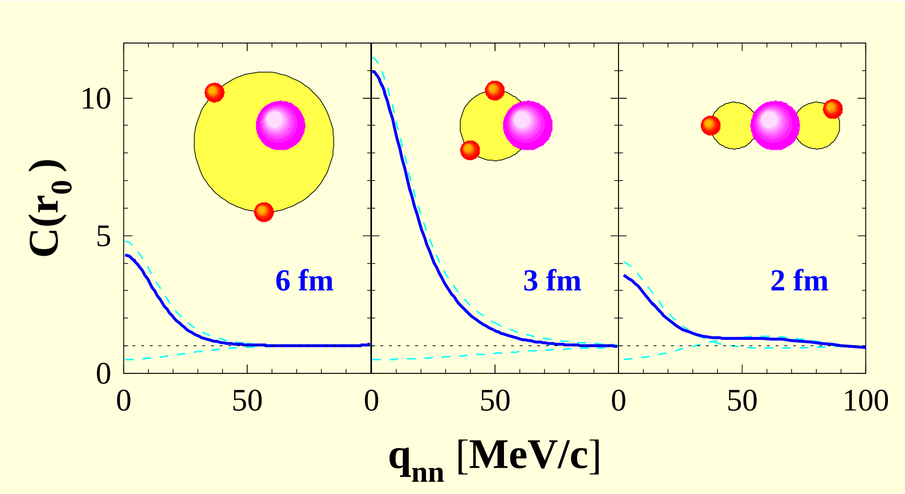

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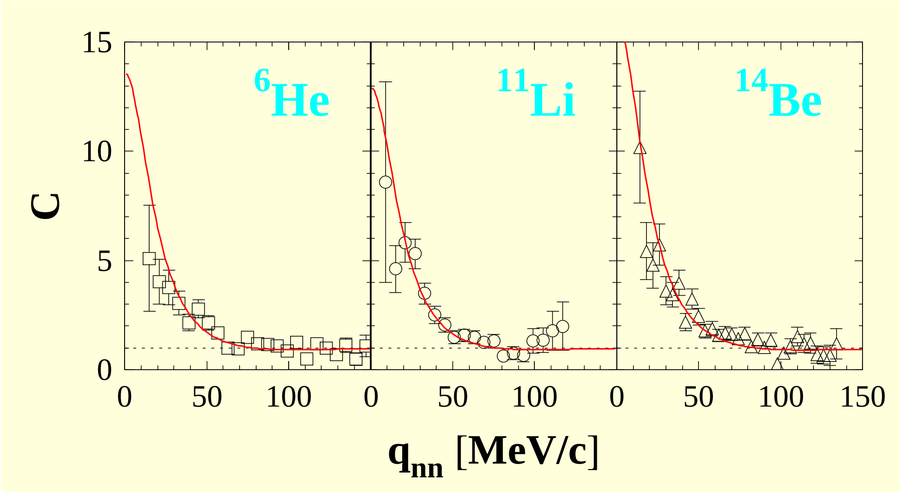
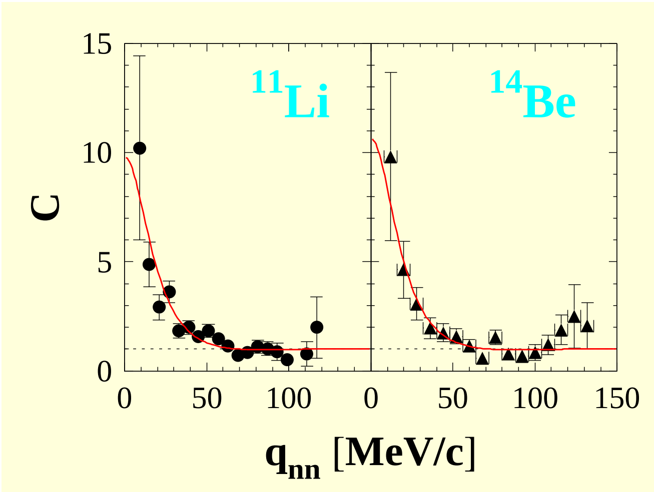


▷ C target …



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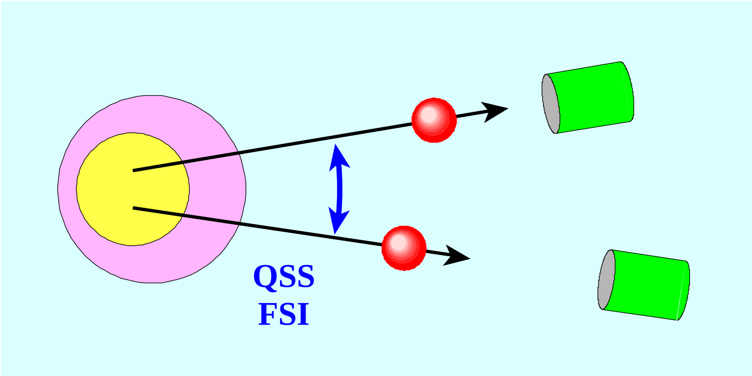
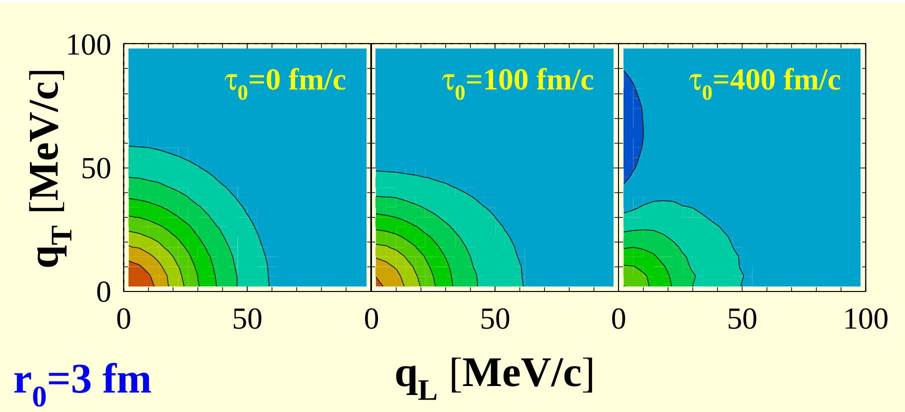


▷ what is the effect of V_{cn} ?



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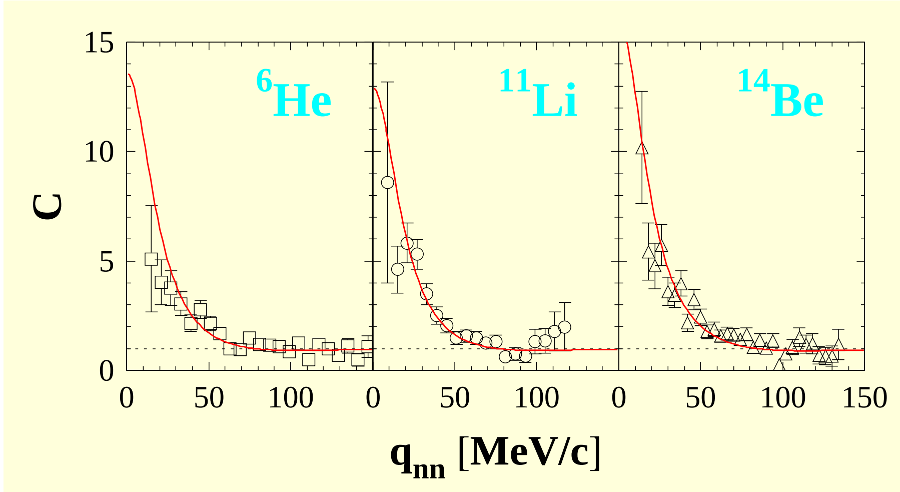

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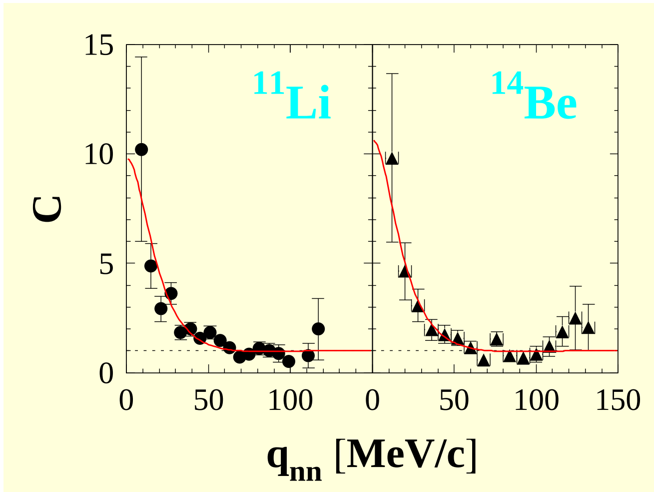
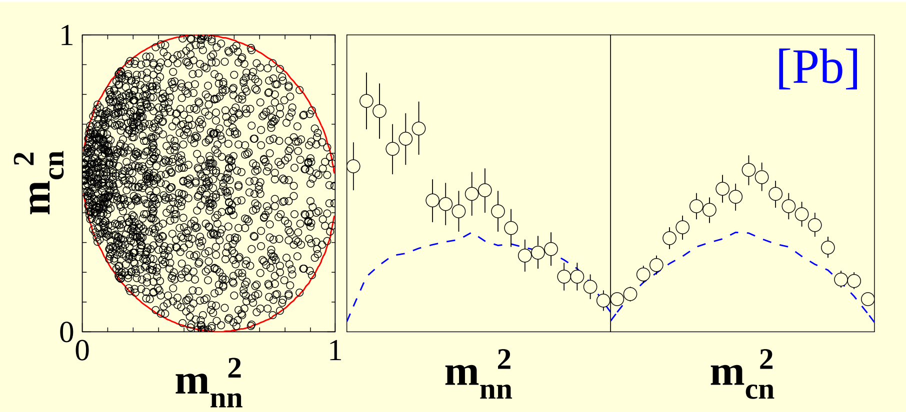
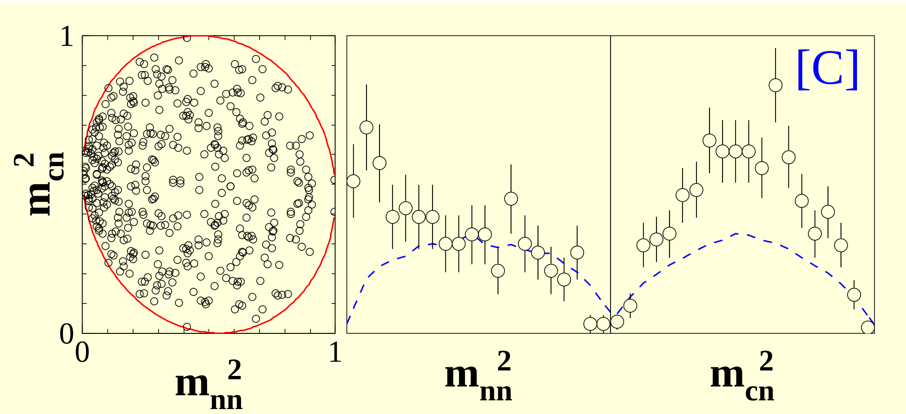


borromean correlations

- ▶ ^{14}Be [FMM et al, PRC 64 (2001) 061301] :
  - ▷ decay ⟶ ^{12}Be+nn
  - ▷ Dalitz plots (core-n vs n-n) :





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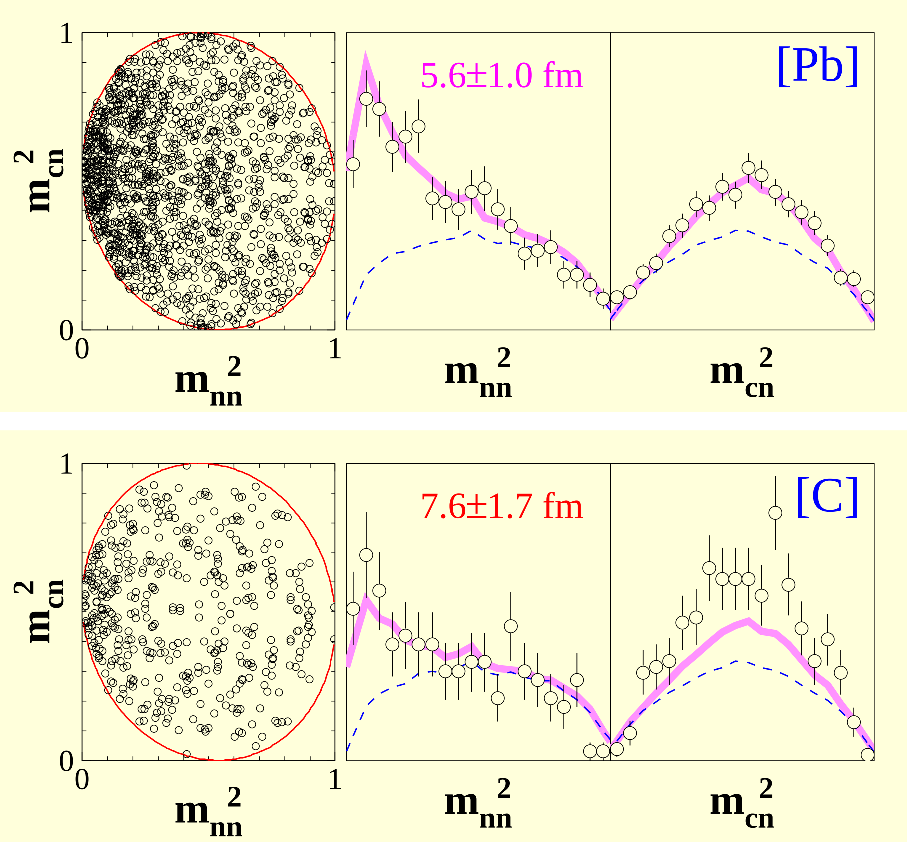

$\rightsquigarrow$ r_{nn}[C] $>$ r_{nn}[Pb] ???

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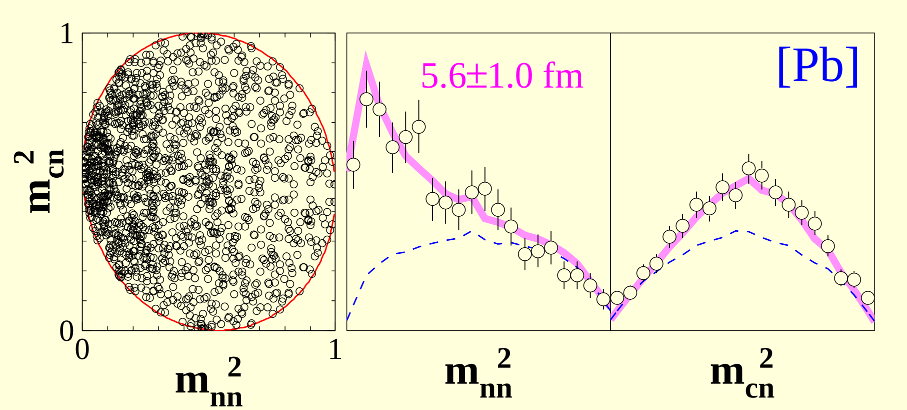

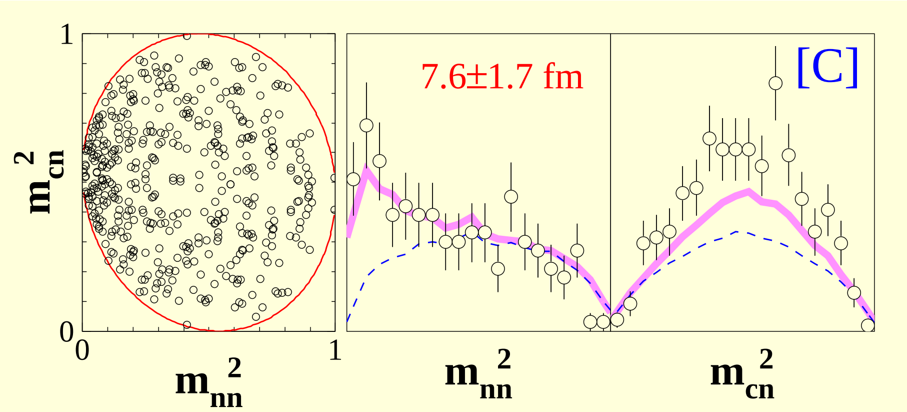

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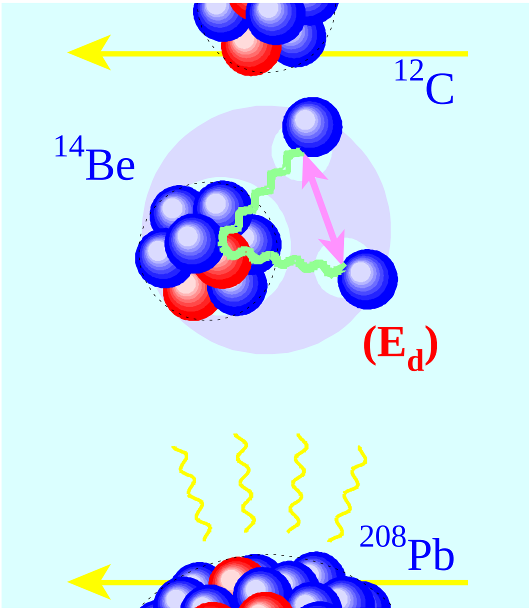
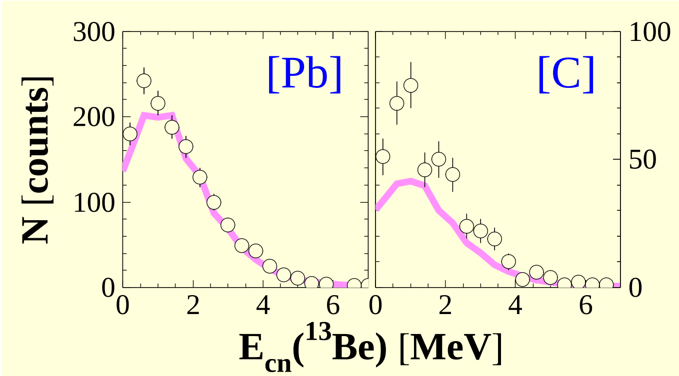
▶ core-n resonances :





$\rightsquigarrow$ $r_{nn}^{rms} = r_{nn}$[Pb] !

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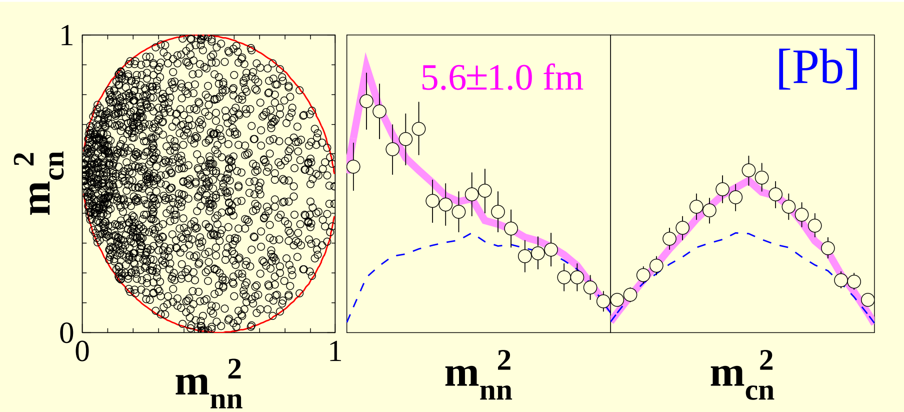

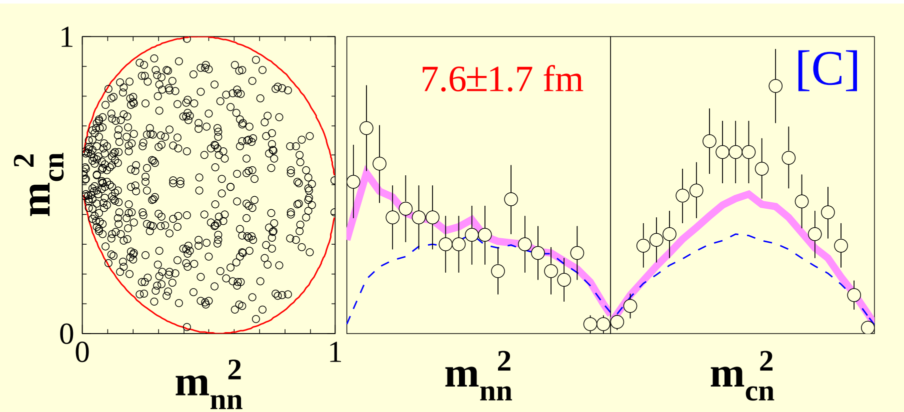

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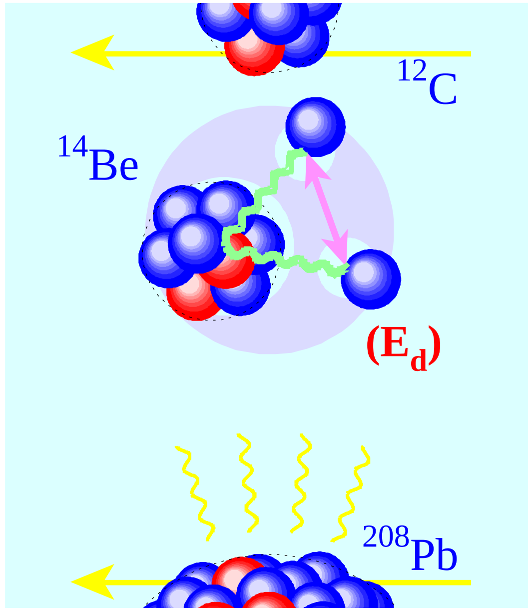
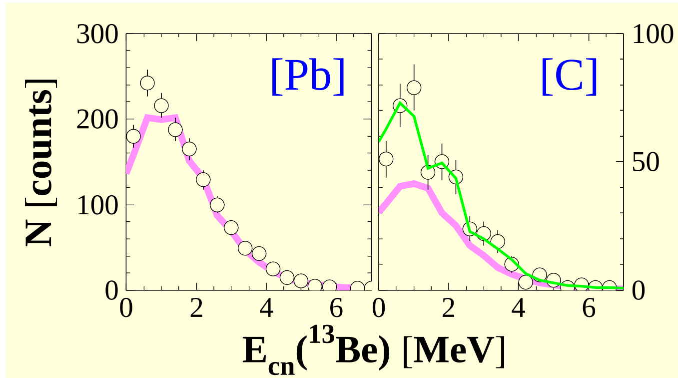
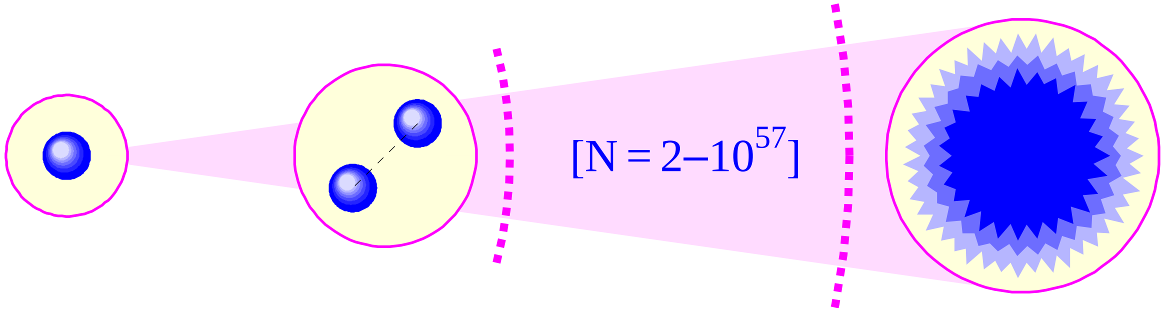




$\rightsquigarrow$ $r_{nn}^{rms} = r_{nn}$[Pb] !

$\rightsquigarrow$ E_{cn} + $\langle \tau_{cn} \rangle \lessapprox$ 400 fm/c !

neutron clusters : a huge gap



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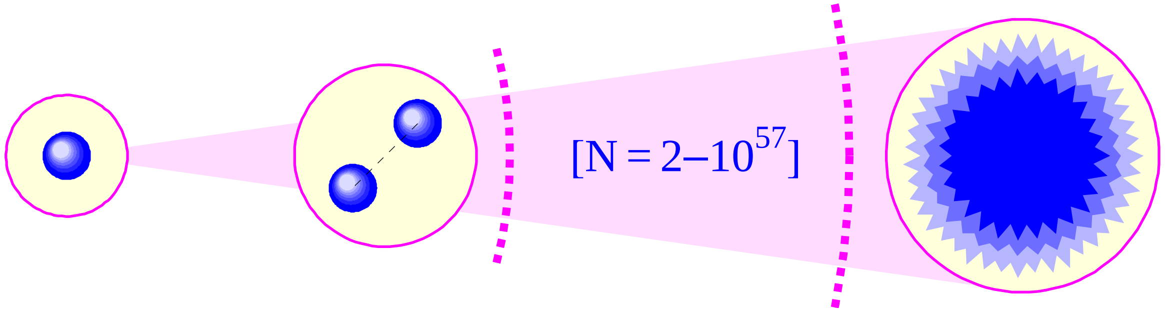
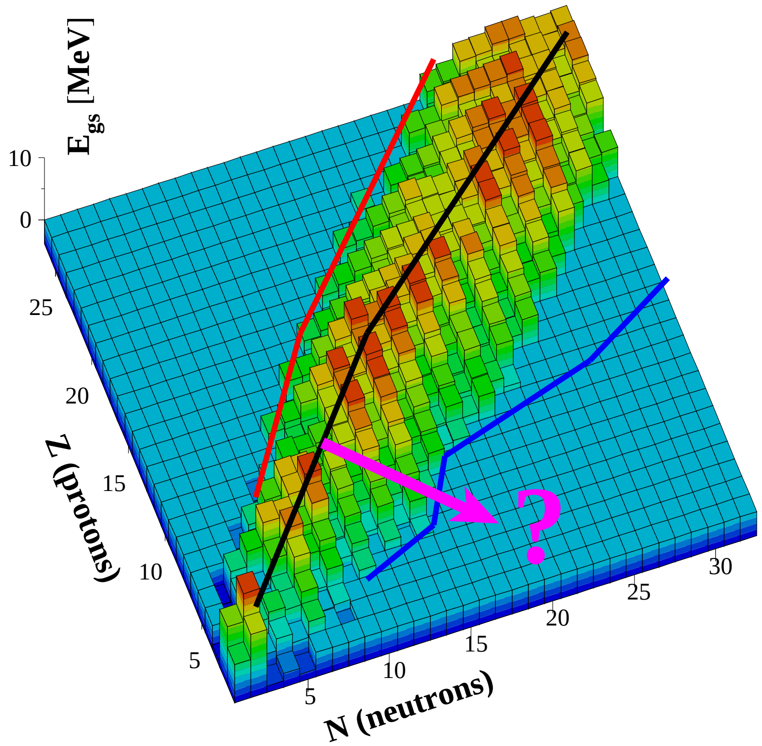
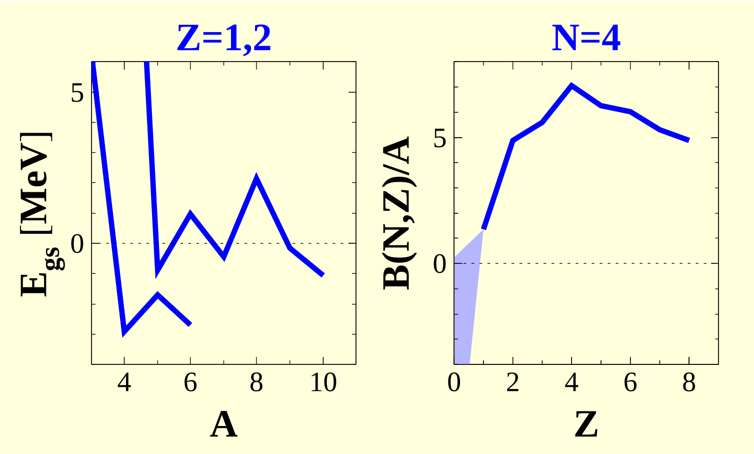




▸ neutron-rich beams : $N \gtrsim 2$?

the landscape in 2001

▶ known masses & asymmetry :



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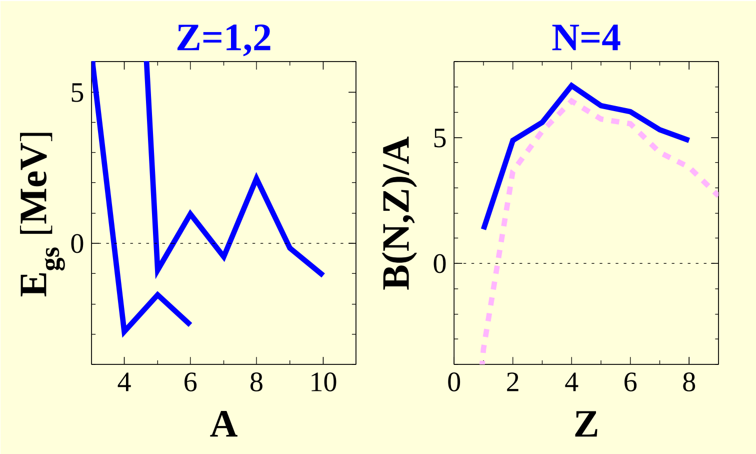

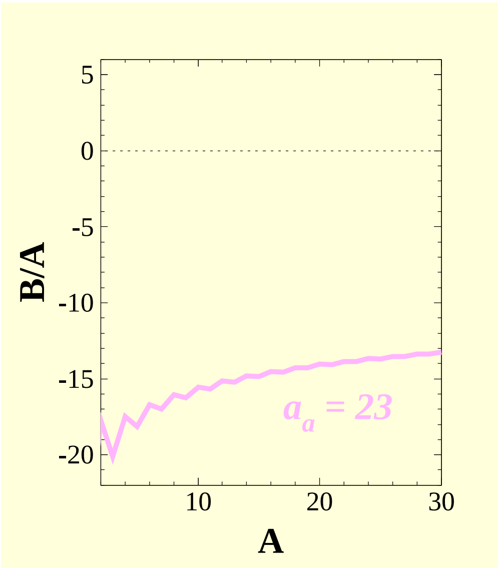

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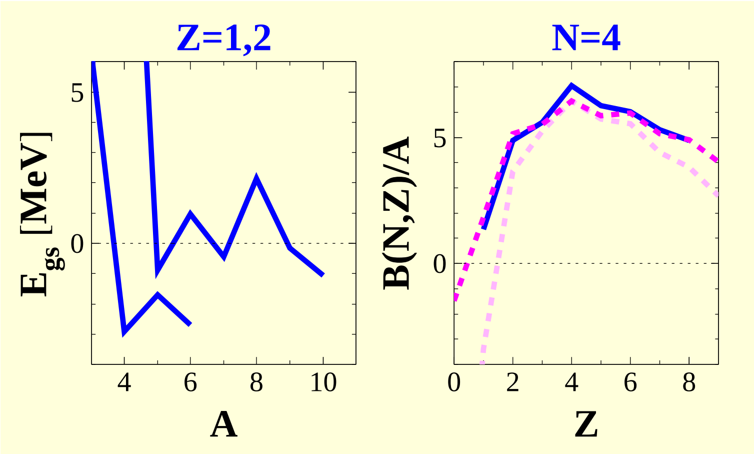

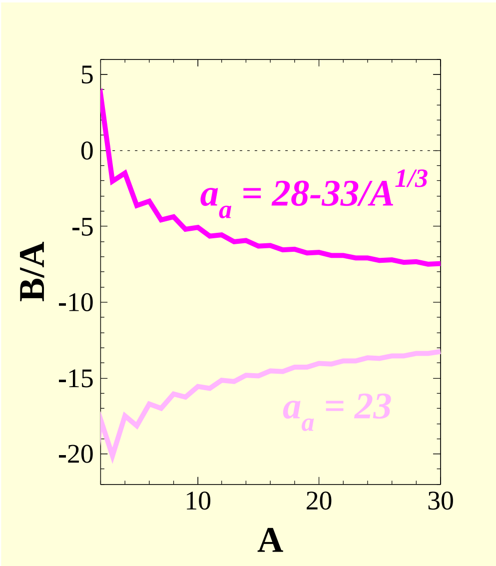

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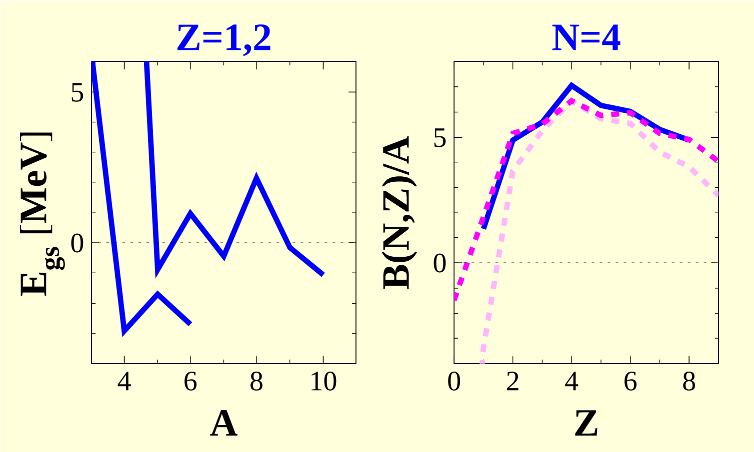
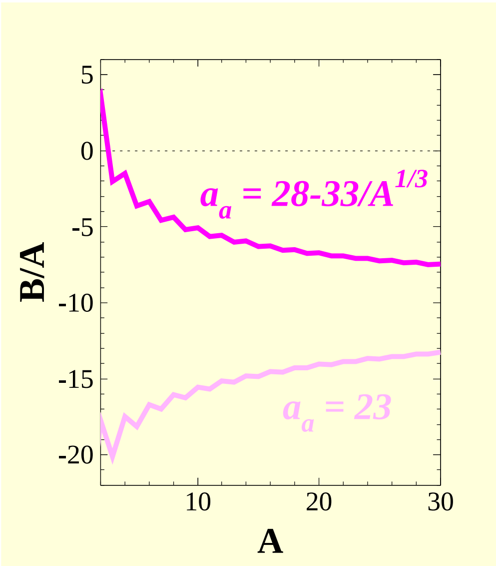
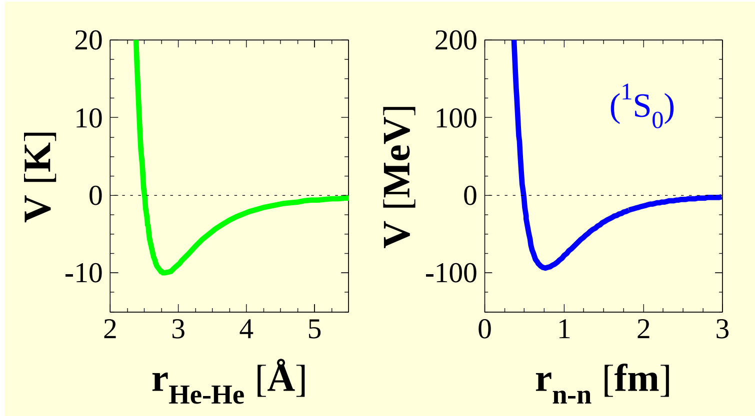
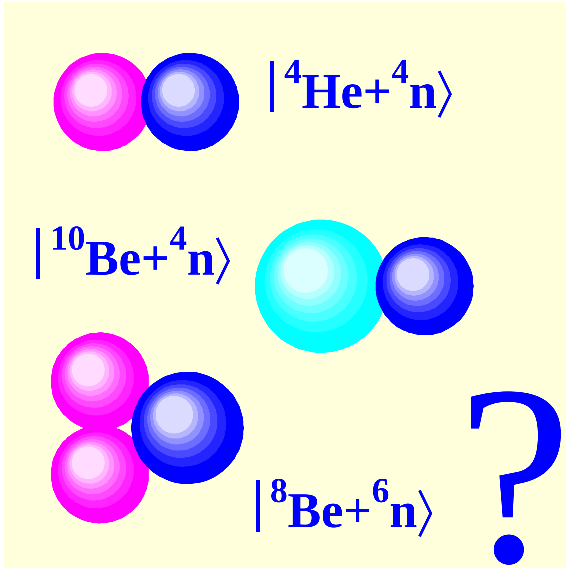




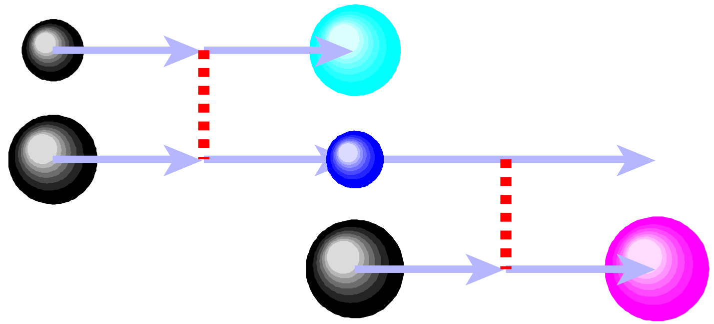
▶ few fermions bound ?



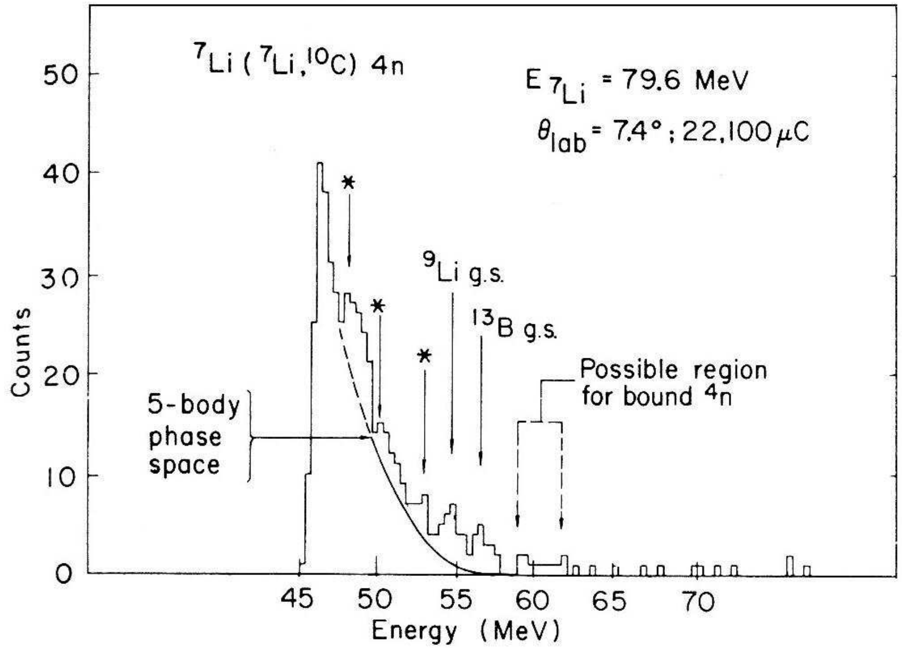


1960s-2000s : a long, unsuccessful quest

- two-step reactions :
  - $p + \mathrm{W} \xrightarrow{(\mathrm{Al})} {}^{A}\mathrm{n} + {}^{70}\mathrm{Zn} \longrightarrow {}^{72}\mathrm{Zn}\ [\,(t,p)\,]$
  - ${}^{208}\mathrm{Pb}\,(\pi^-,\pi^+)\,{}^{4}\mathrm{n} \xrightarrow{({}^{208}\mathrm{Pb})} {}^{212}\mathrm{Pb} + \gamma$



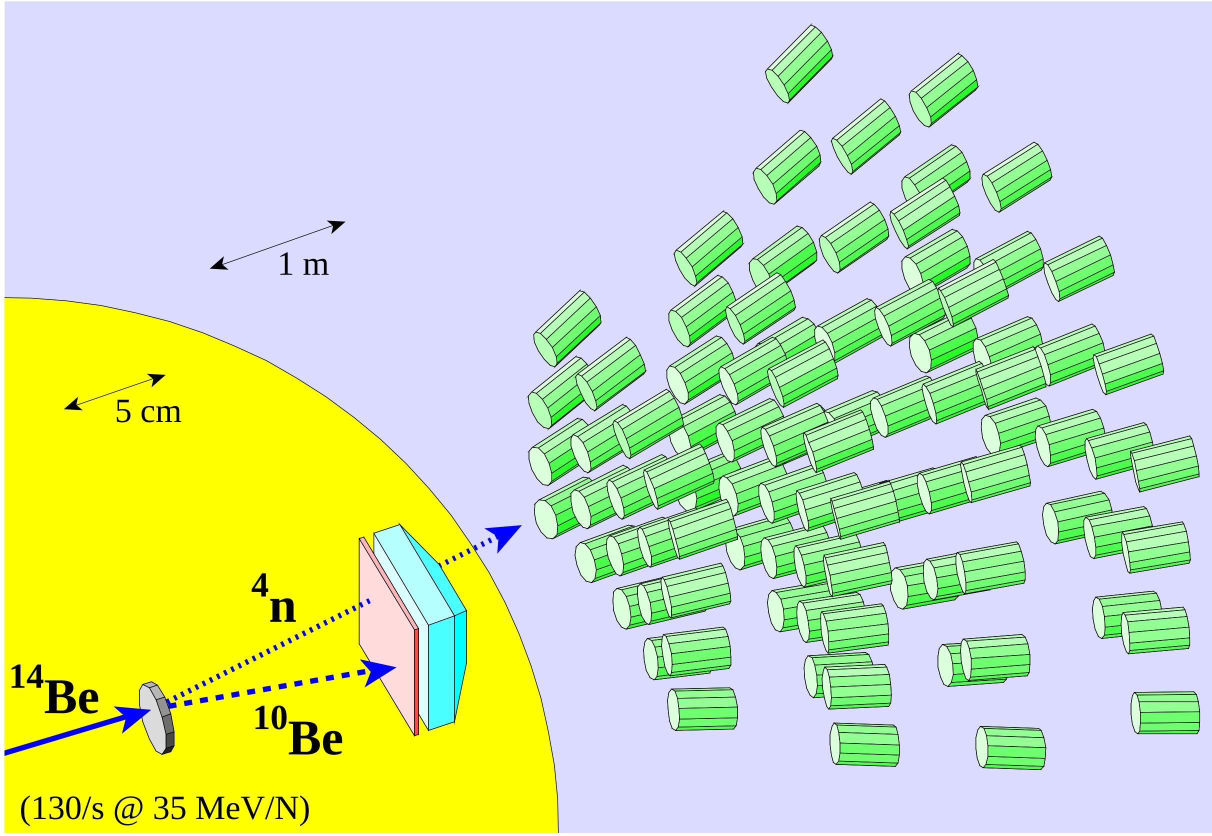
- pion charge exchange :
  - ${}^{3}\mathrm{H}\,(\pi^-,\gamma)\,3n$
  - ${}^{\{3,4\}}\mathrm{He}\,(\pi^-,\pi^+)\,\{3,4\}n$
- multinucleon transfer :
  - ${}^{7}\mathrm{Li} + {}^{11}\mathrm{B} \longrightarrow {}^{14}\mathrm{O} + 4n$
  - ${}^{7}\mathrm{Li} + {}^{7}\mathrm{Li} \longrightarrow {}^{\{10,11\}}\mathrm{C} + \{4,3\}n$



⇝ bcks + cross-sections ...

the principle ...

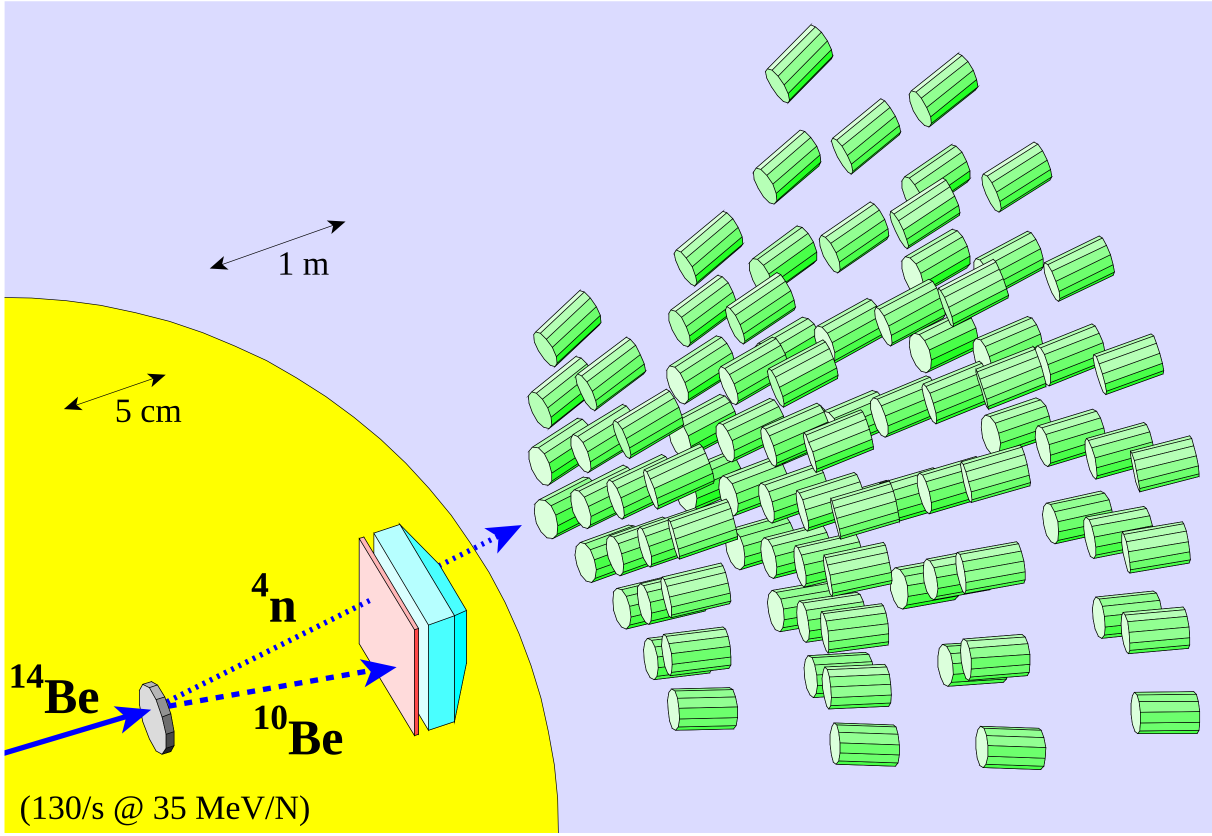
▶ $|^{14}\text{Be}\rangle \equiv a\,|^{10}\text{Be} + {}^{4}\text{n}\rangle + \cdots$

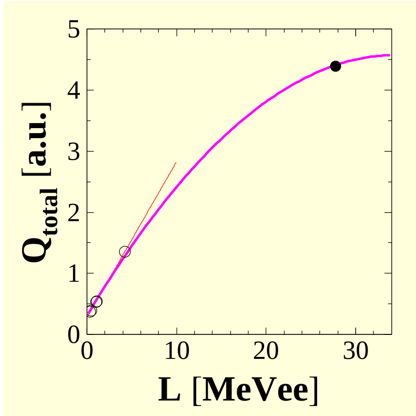


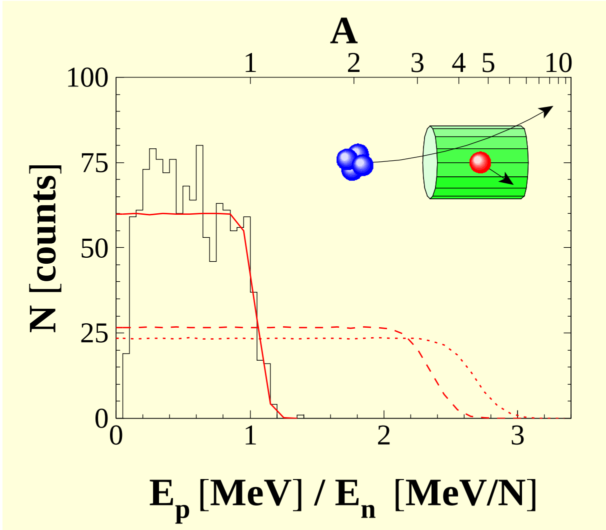
▷ effective + clean

the principle …

▶ $|^{14}\mathrm{Be}\rangle \equiv a\,|^{10}\mathrm{Be} + {}^{4}\mathrm{n}\rangle + \cdots$



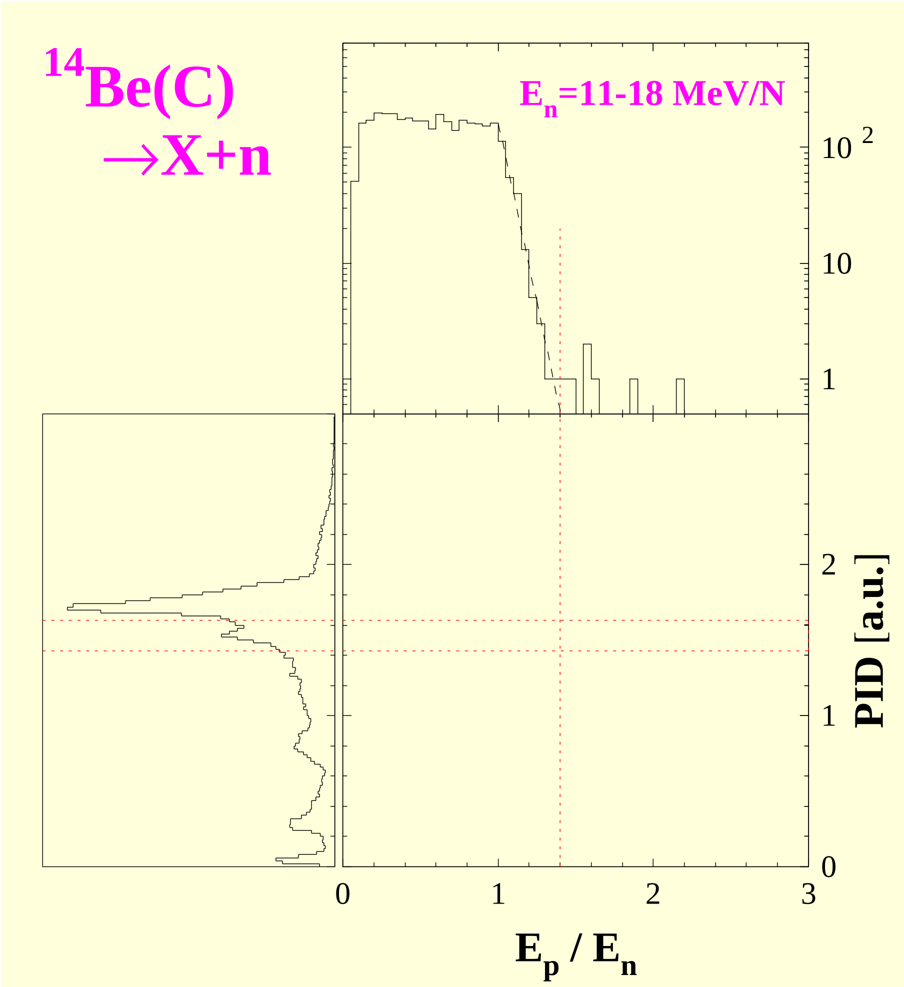




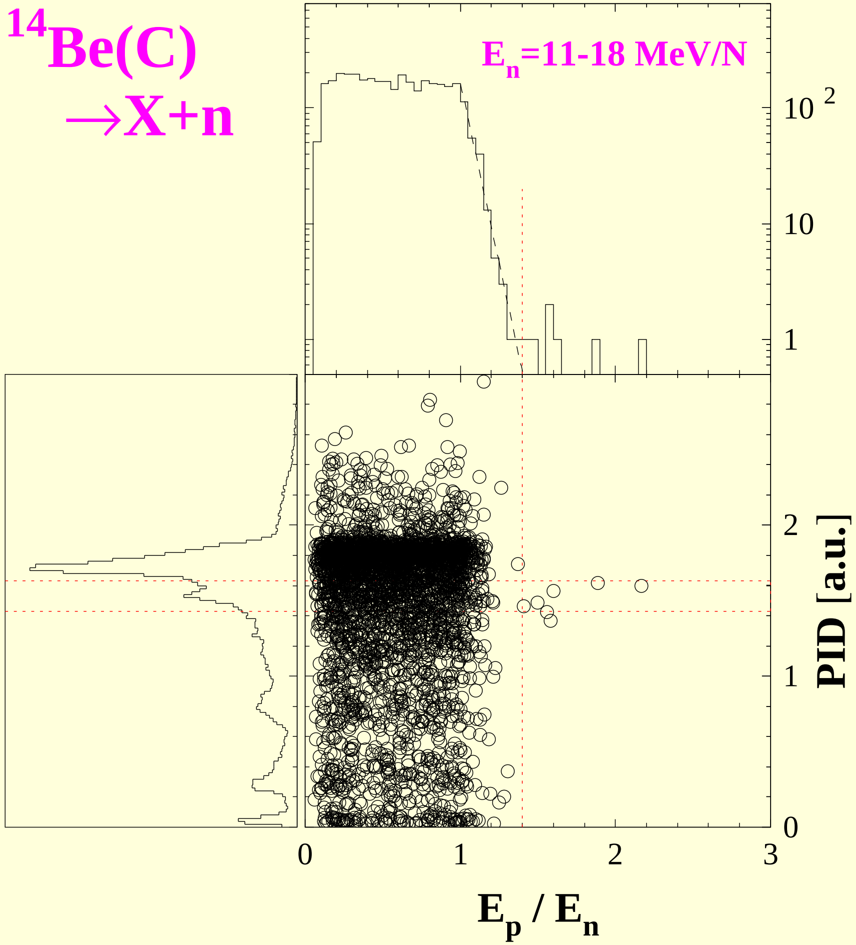
▷ effective + clean + sensitive !!!

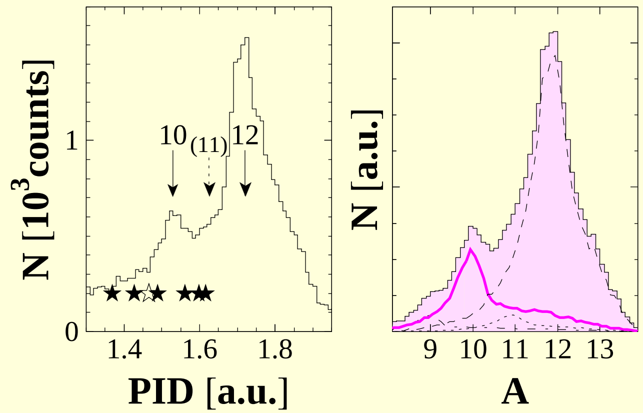
▷ saturation (sensitive to low E_p) …

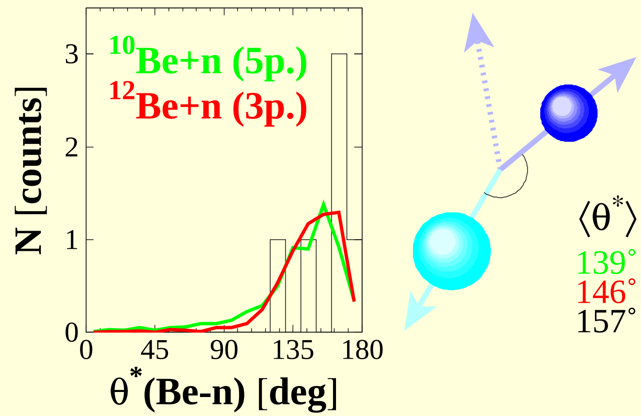
… and the results



… and the results



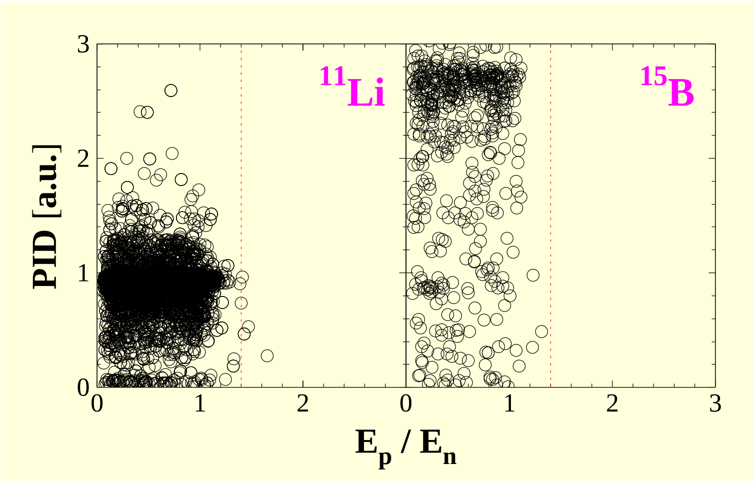


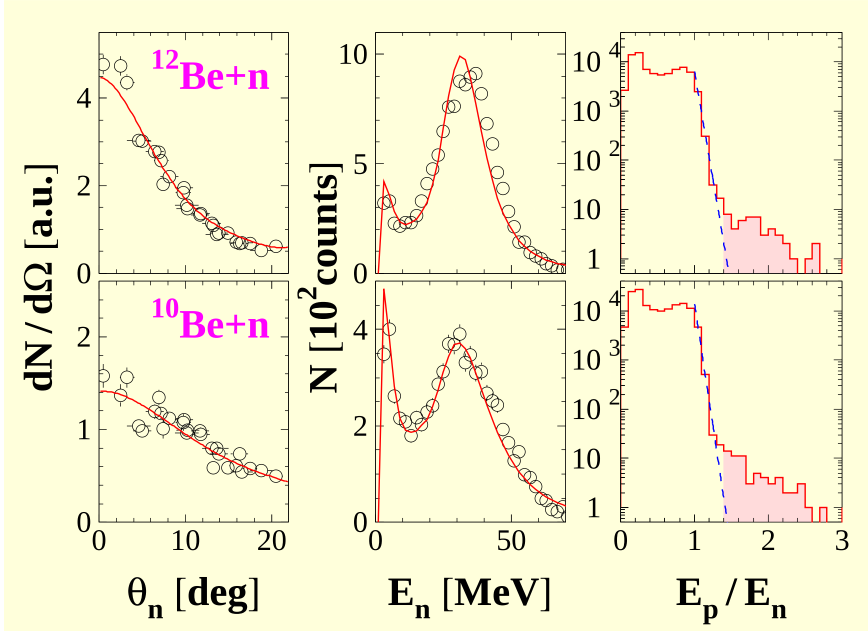


▷ looks like : $^{14}\mathrm{Be} \xrightarrow{(C)} {}^{10}\mathrm{Be} + {}^{4}\mathrm{n}$

“standard” alternative sources

▶ other beam particles :

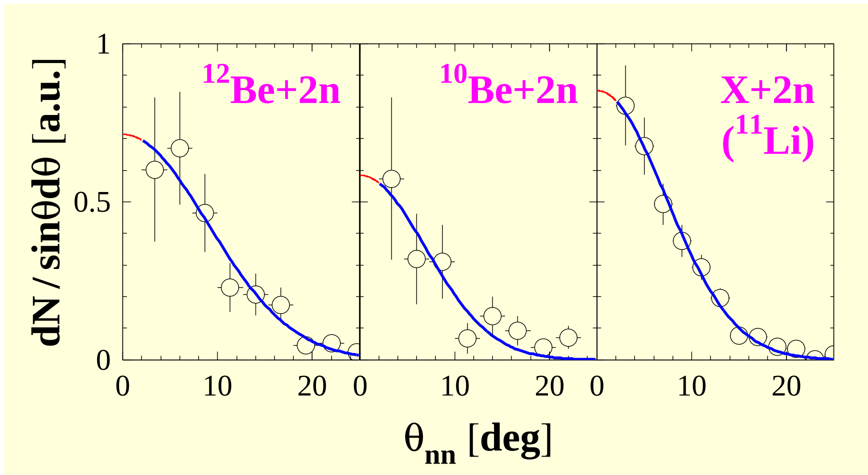




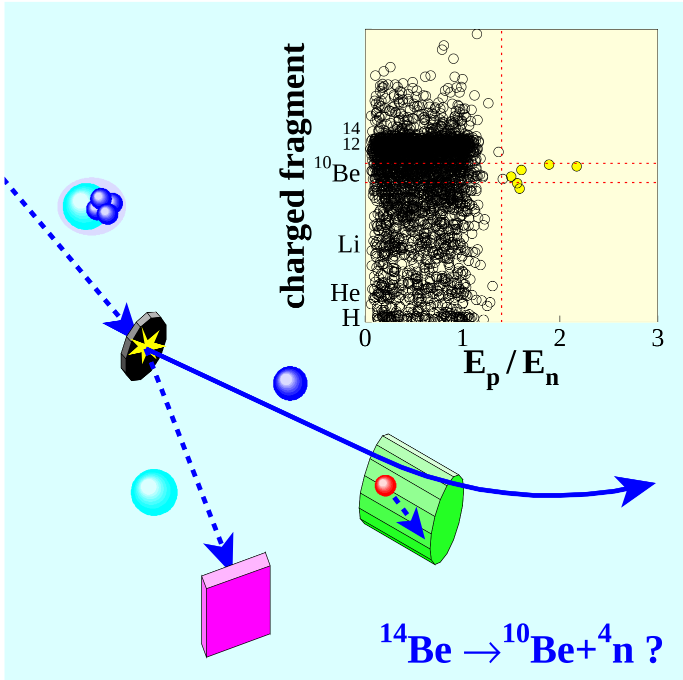
▶ estimated pileup $[xn]$:

channel	N_{2n}^{exp}	$N_{2n}^{(12)}$	$N_{2n}^{(\text{sim})}$	$N_{2n}^{(nn)}$
(^{11}Li, X)	4	<6.0	~3.3	<7.0
(^{15}B, X)	0	<0.5	~0.3	<0.9
(^{14}Be, ^{12}Be)	0	–	0.8	<1.2
(^{14}Be, ^{10}Be)	6	<0.5	0.2	<0.8

[FMM et al, PRC 65 (2002) 044006]



trigger of experiments and calculations



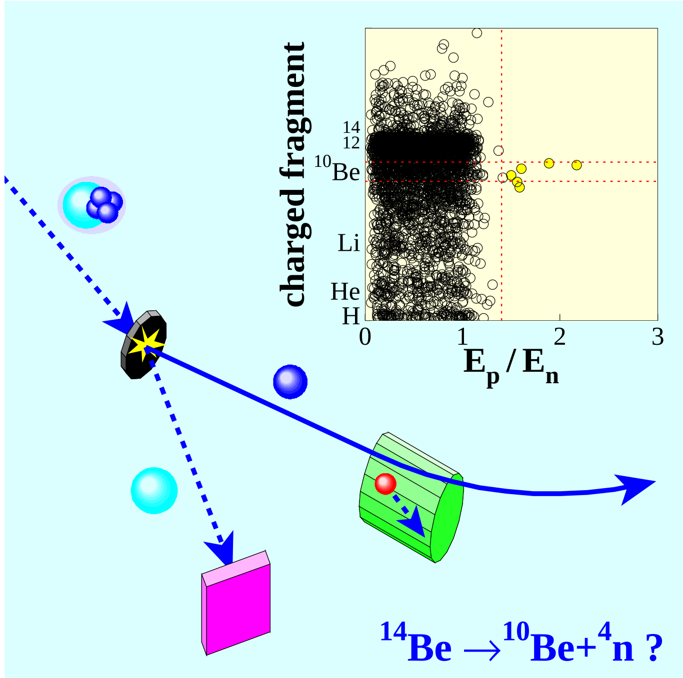
$$^{14}\text{Be} \xrightarrow{(\text{C})} {}^{10}\text{Be} + {}^{4}\text{n} \qquad (\text{'01,'02})$$

$$^{8}\text{He} \xrightarrow{(\text{C})} {}^{4}\text{He} + {}^{4}\text{n} \qquad (\text{'02})$$

$$^{12/14}\text{Be} \xrightarrow{(\text{C})} 2\alpha + {}^{4/6}\text{n} \qquad (\text{'02})$$

$$^{8}\text{He} \xrightarrow{(d)} {}^{4}\text{He} + d\ [+{}^{4}\text{n}] \qquad (\text{'04})$$

trigger of experiments and calculations



$$^{14}\text{Be} \xrightarrow{(\text{C})} {}^{10}\text{Be} + {}^{4}\text{n} \quad ('01,'02)$$

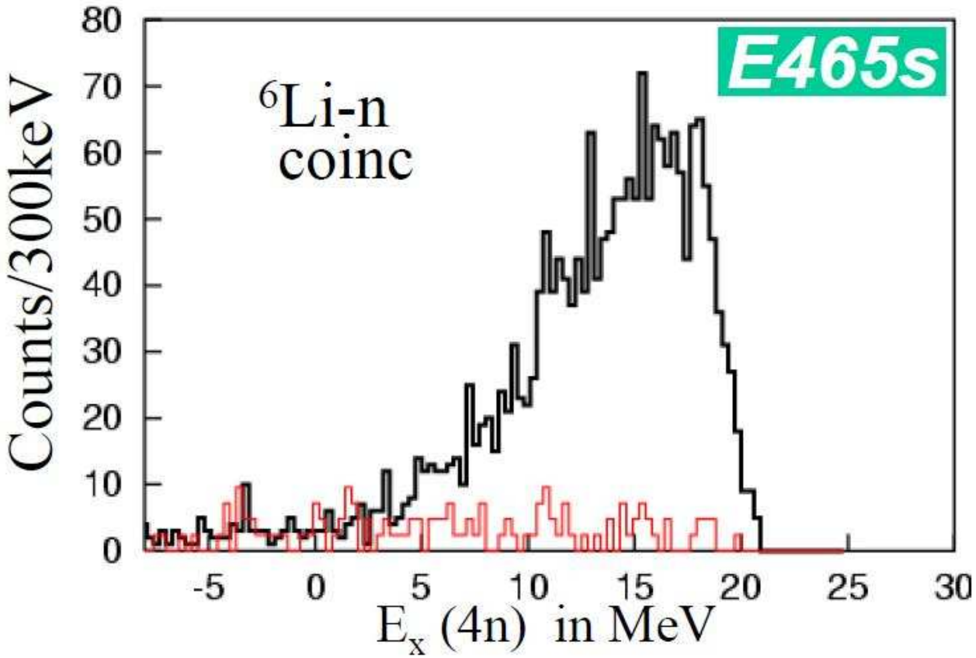
$$^{8}\text{He} \xrightarrow{(\text{C})} {}^{4}\text{He} + {}^{4}\text{n} \quad ('02)$$

$$^{12/14}\text{Be} \xrightarrow{(\text{C})} 2\alpha + {}^{4/6}\text{n} \quad ('02)$$

$$^{8}\text{He} \xrightarrow{(d)} {}^{4}\text{He} + d\ [+{}^{4}\text{n}] \quad ('04)$$

- ▶ transfer [Beaumel] :

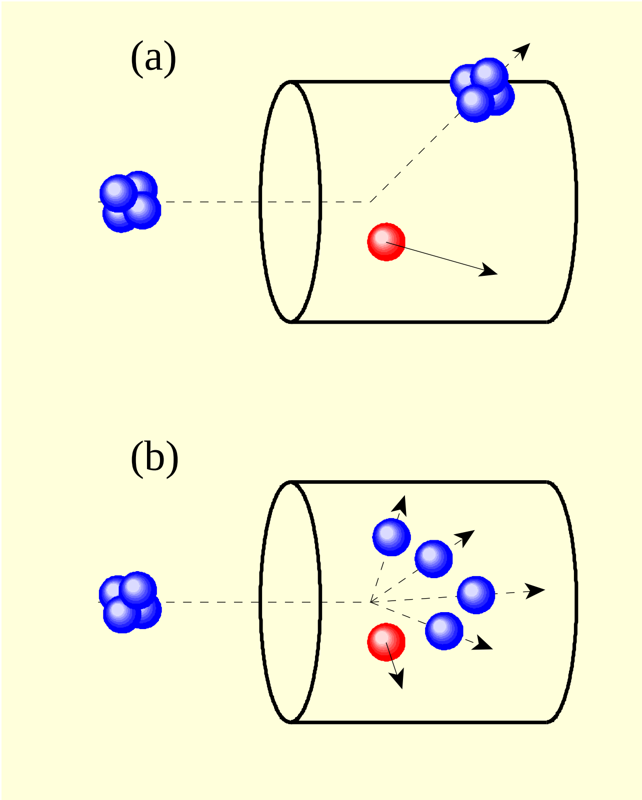
$$^{8}\text{He} \xrightarrow{(d)} {}^{6}\text{Li}\ [+{}^{4}\text{n}] \quad ('02,'04)$$



- ▶ "modern" calculations :
  - ▷ bound/resonance ? [Pieper,Carbonell]
  - ▷ (^{4}n, p) scattering [Bertulani]

about the ^{4}n candidate events

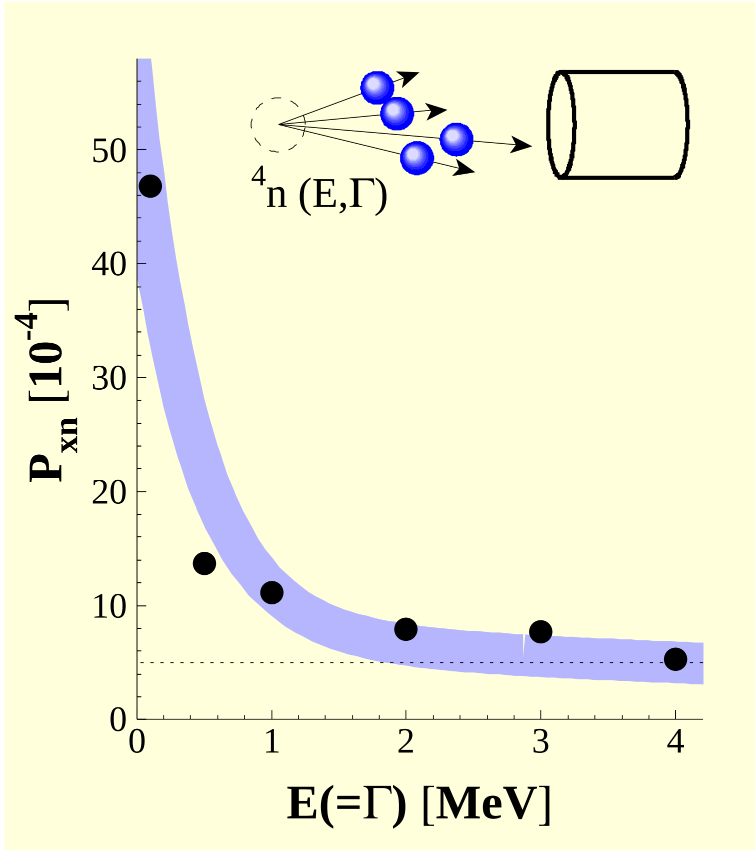
▶ elastic (^{4}n, p) scattering ?



▷ $\sigma_{breakup} \sim \sigma_{np} \sim 1$ b …

▷ $P_n = 0.4 \Rightarrow \quad P_{2,3,4n} = 0.52$!

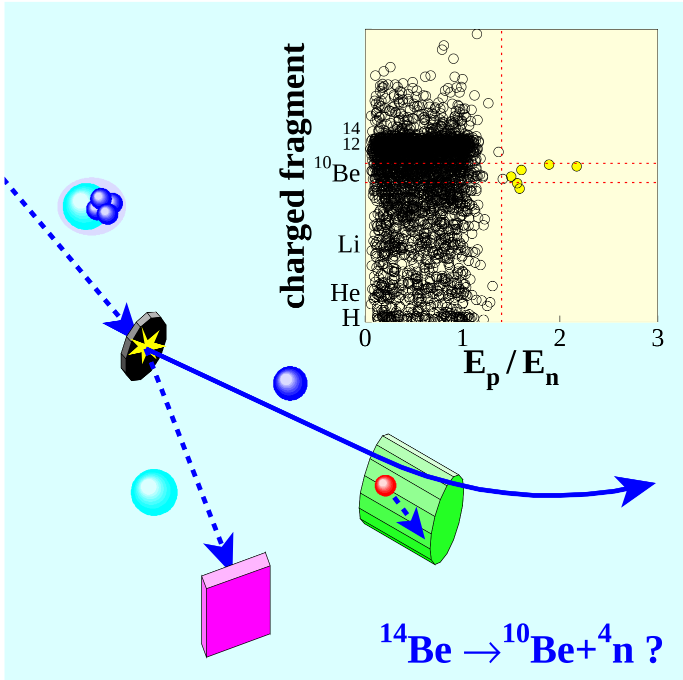
▶ P_{xn} due to ^{4}n resonance :



▷ $P_{xn} \times 10$!

▷ 4-n phase space : lower limit …

new results : Bouchat, PRELIMINARY



$$^{14}\text{Be} \xrightarrow{(\text{C})} {}^{10}\text{Be} + {}^{4}\text{n} \qquad ('01, '02)$$

$$\boxed{^{8}\text{He}} \xrightarrow{(\text{C})} {}^{4}\text{He} + {}^{4}\text{n} \qquad ('02)$$

$$^{12/14}\text{Be} \xrightarrow{(\text{C})} 2\alpha + {}^{4/6}\text{n} \qquad ('02)$$

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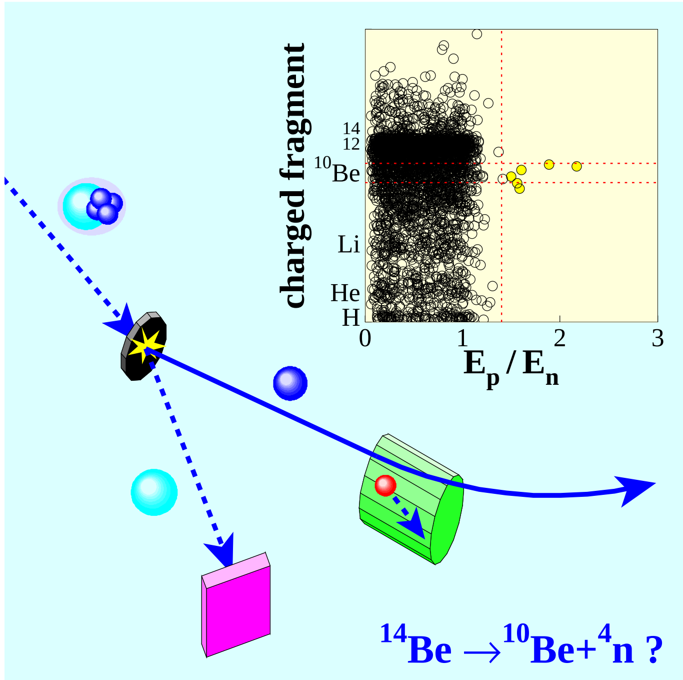
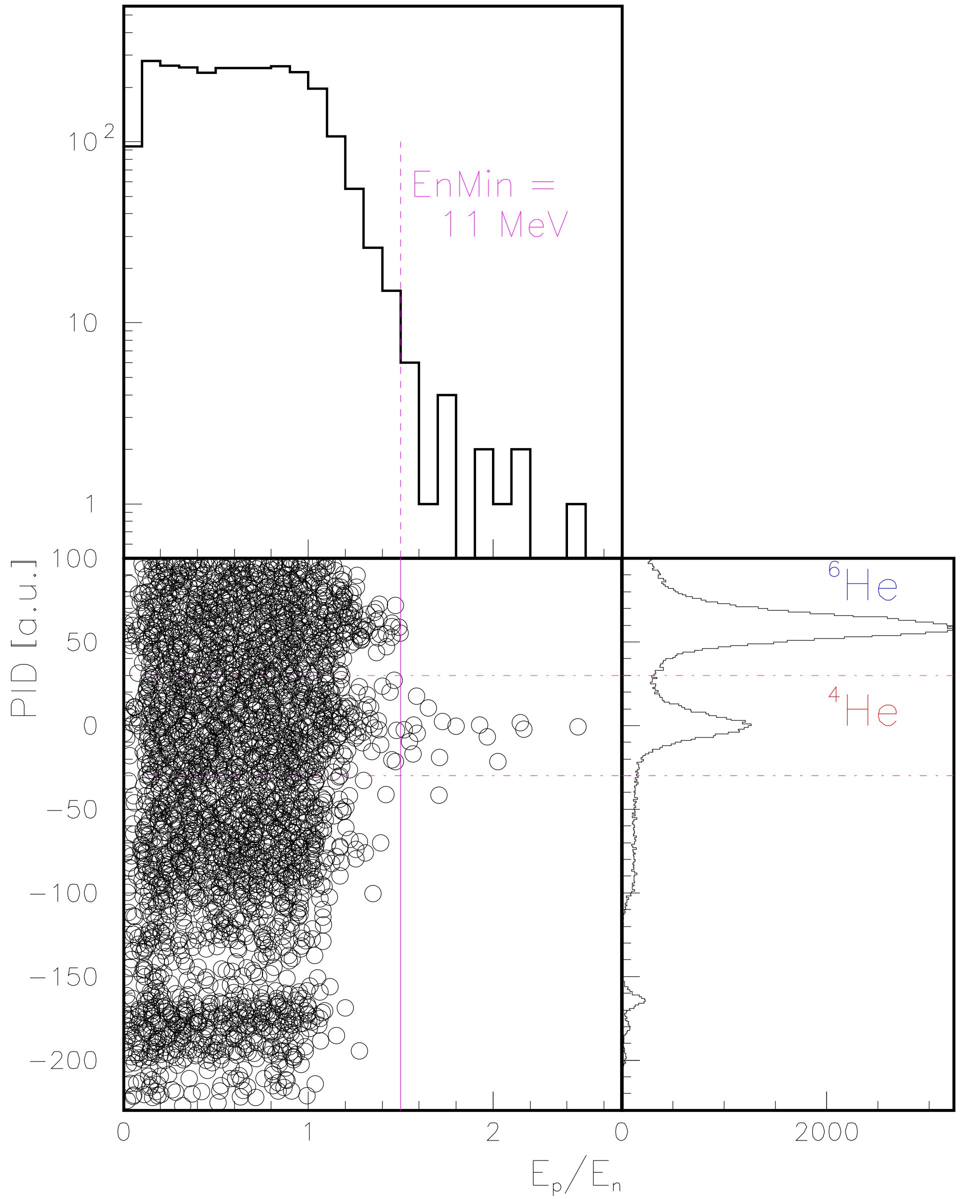
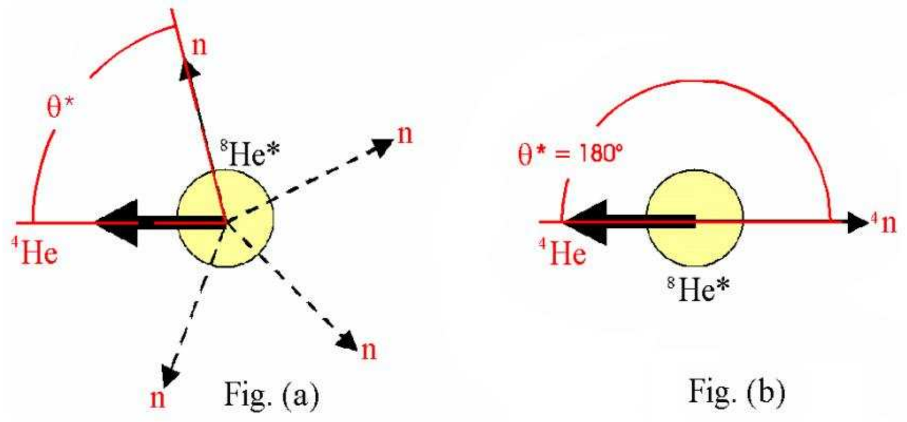
new results : Bouchat, PRELIMINARY



^{14}Be $\xrightarrow{(C)}$	^{10}Be + ^{4}n	('01,'02)
^{8}He $\xrightarrow{(C)}$	^{4}He + ^{4}n	('02)
$^{12/14}$Be $\xrightarrow{(C)}$	2α + $^{4/6}$n	('02)
^{8}He $\xrightarrow{(d)}$	^{4}He + d [+^{4}n]	('04)



angular correlations



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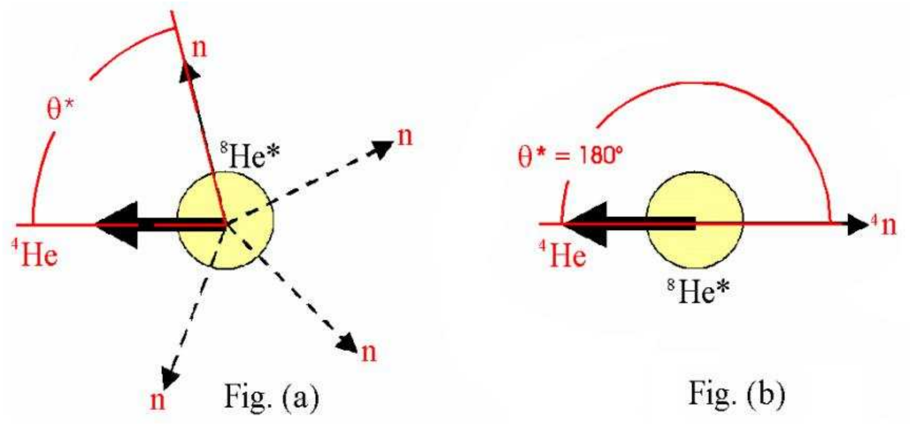

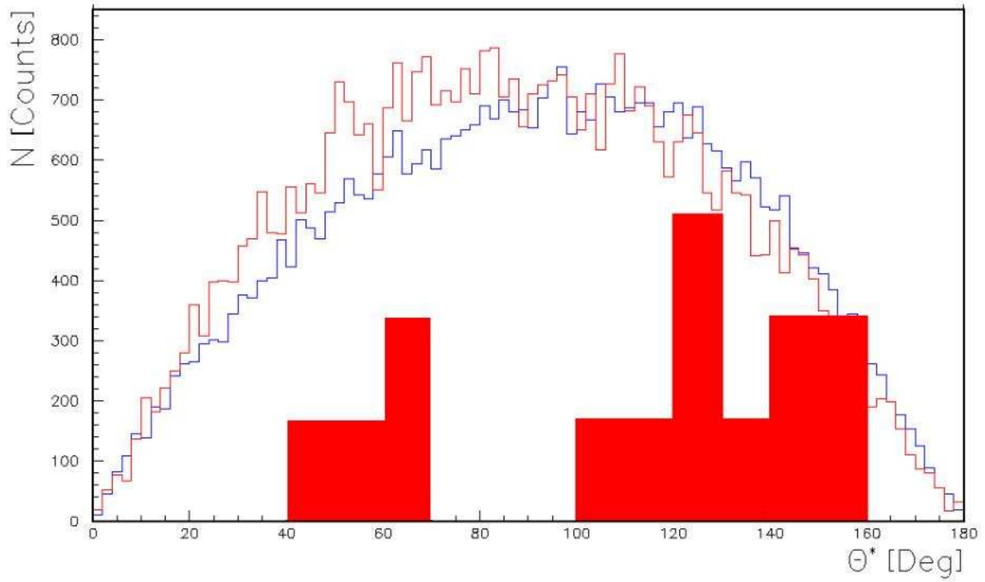

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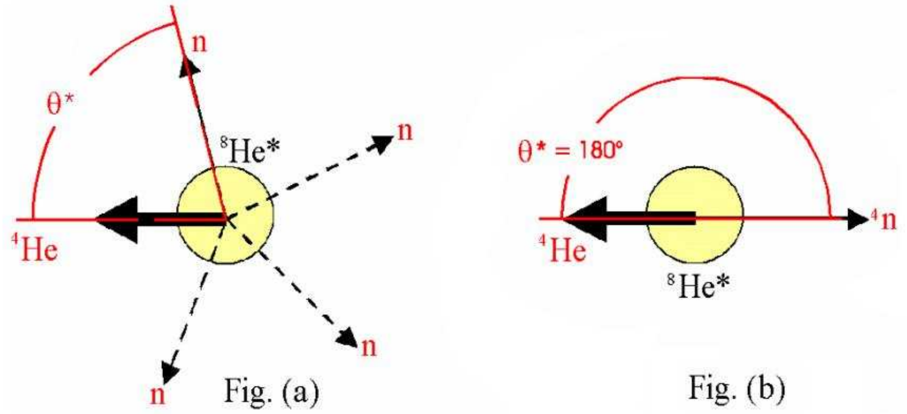

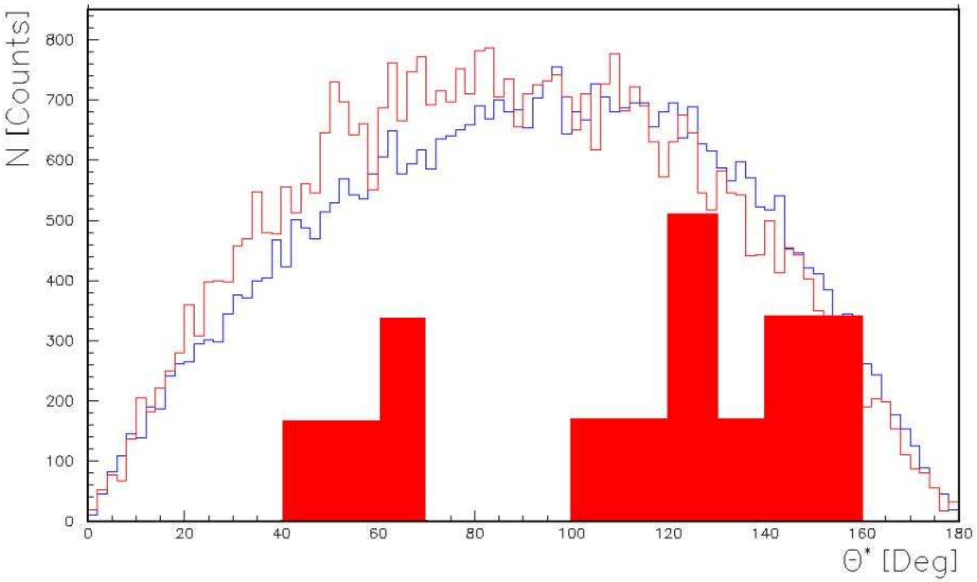

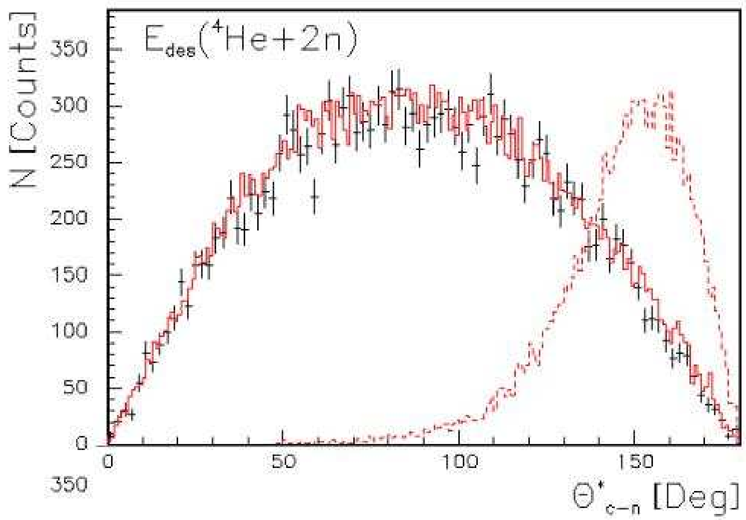

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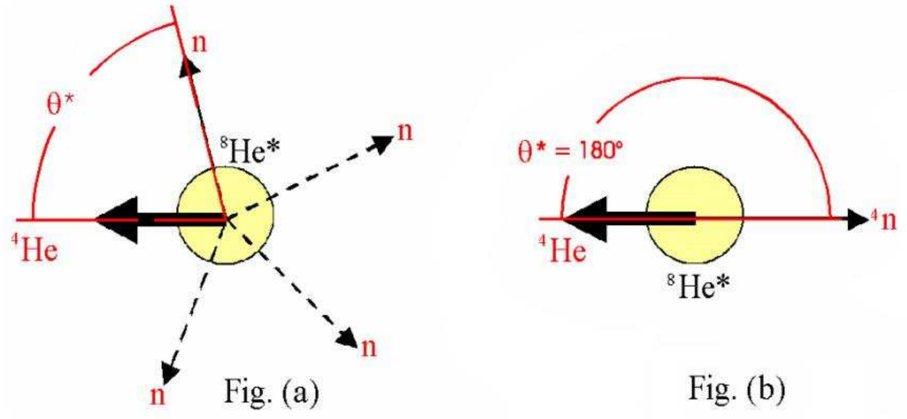
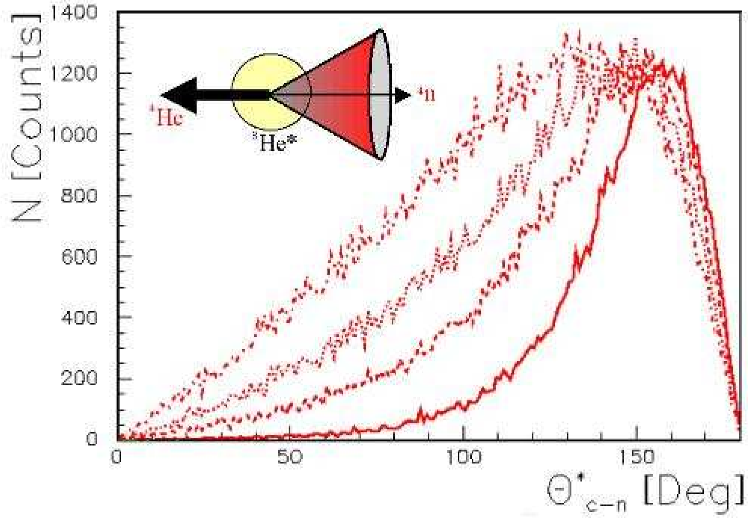
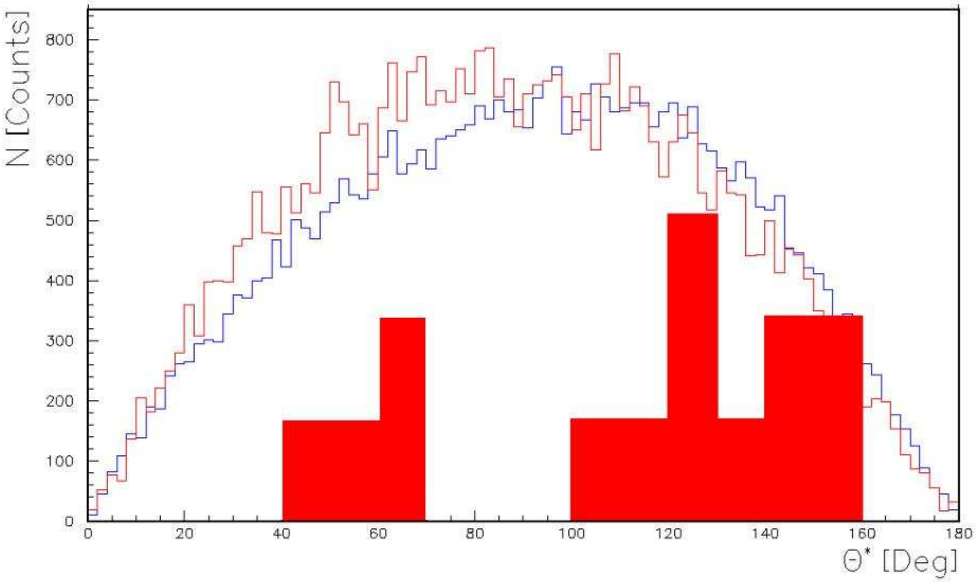
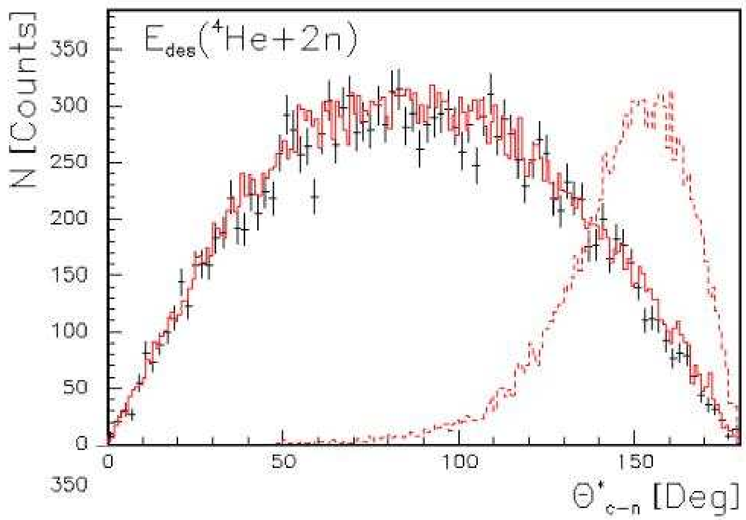


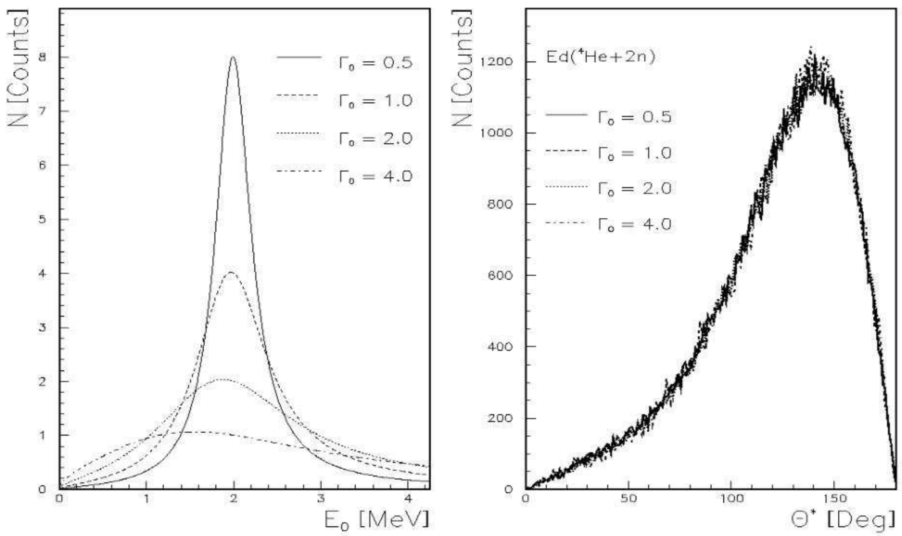






PRELIMINARY conclusions & outlook

- ^{8}He from SPIRAL :
  - ▷ clean ^{4}He identification
  - ▷ 14 events ! $(E_p/E_n > 1.4)$
  - ▷ no saturation !
    - ⇝ angular correlations
    - ⇝ sensitive to "any" state ???



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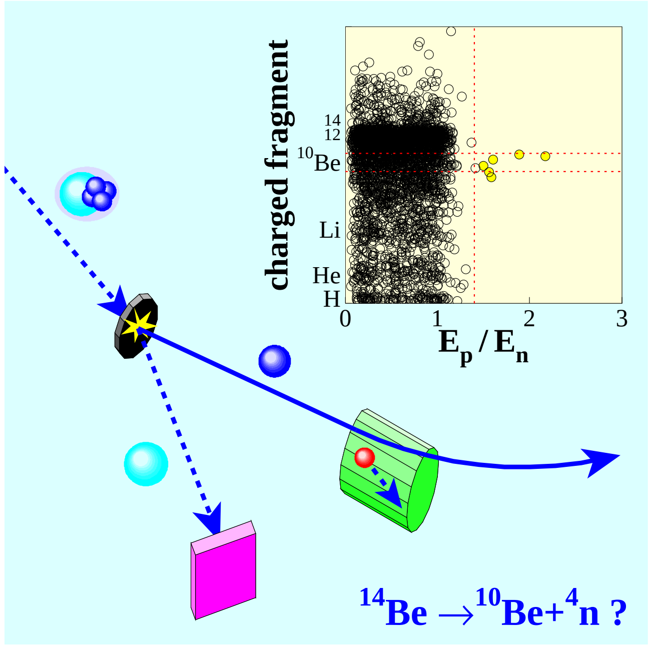


- DEMON @ GANIL ('05,'06) :

$$^{15}\text{B} \xrightarrow{(\text{C})} {}^{14}\text{Be}^* \longrightarrow {}^{10/8}\text{Be} + {}^{4/6}\text{n}$$

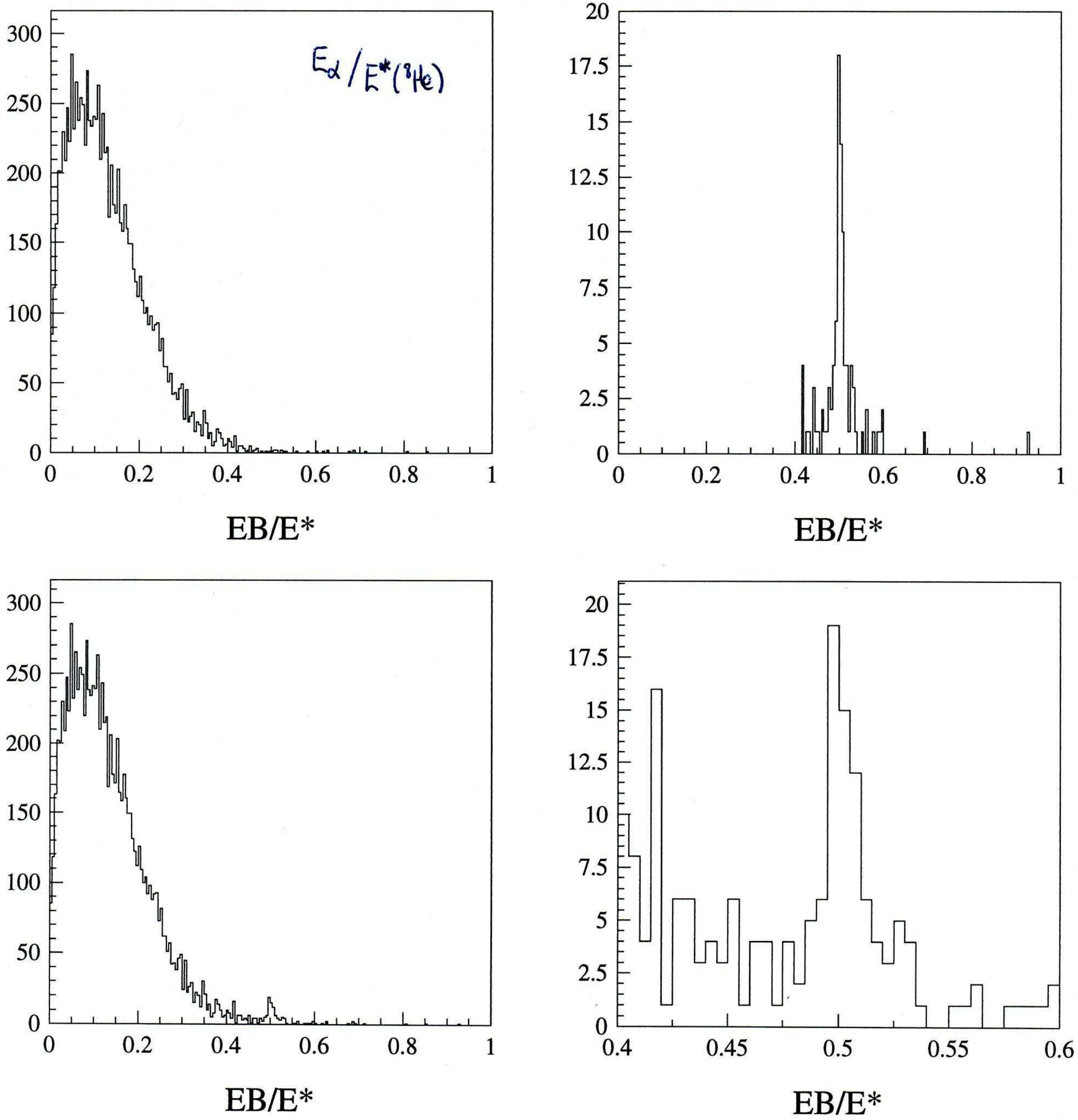
- ⇝ higher statistics !
- ⇝ analysis in progress …

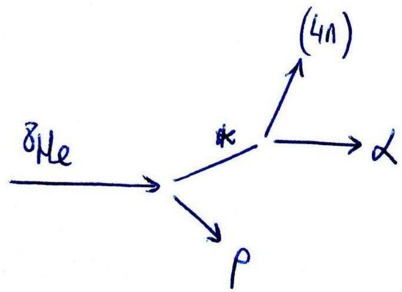
⇝ ^{17}B : $Q_{\beta 4n} = 9$ MeV

⇝ ^{19}B : $Q_{\beta 4/6n} \sim 17/8$ MeV
$S_{4n} \sim 2$ MeV !!!

⇝ ^{8}He : $S_{\alpha\,[+4n]} = 3.1$ MeV
$S_{\alpha\,[+^4n]} < 3.1$???

alpha knock-out … (?)





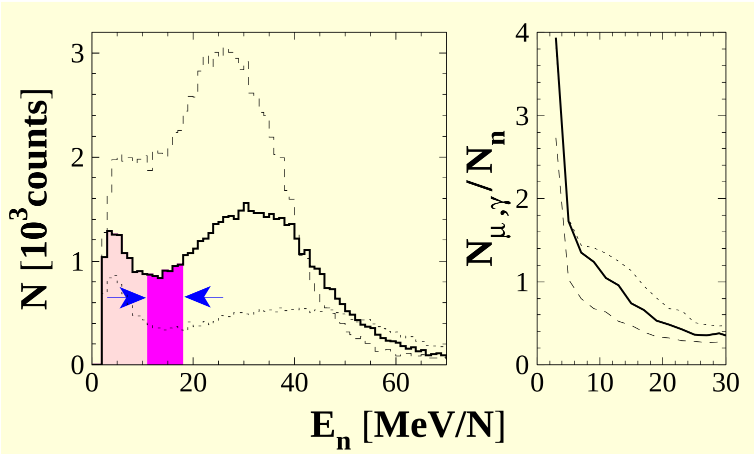
8He @ (15 ± 0.1) MeV/N

Γ(4n) = 1 %

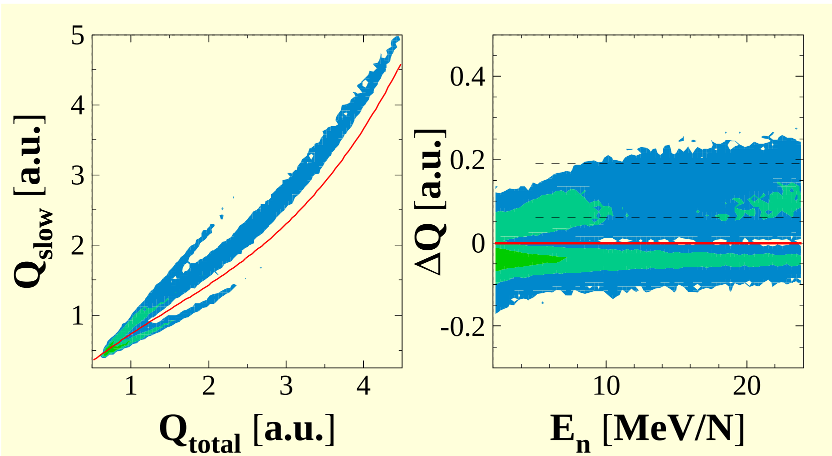
ΔEp = 5 %

saturation and energy range

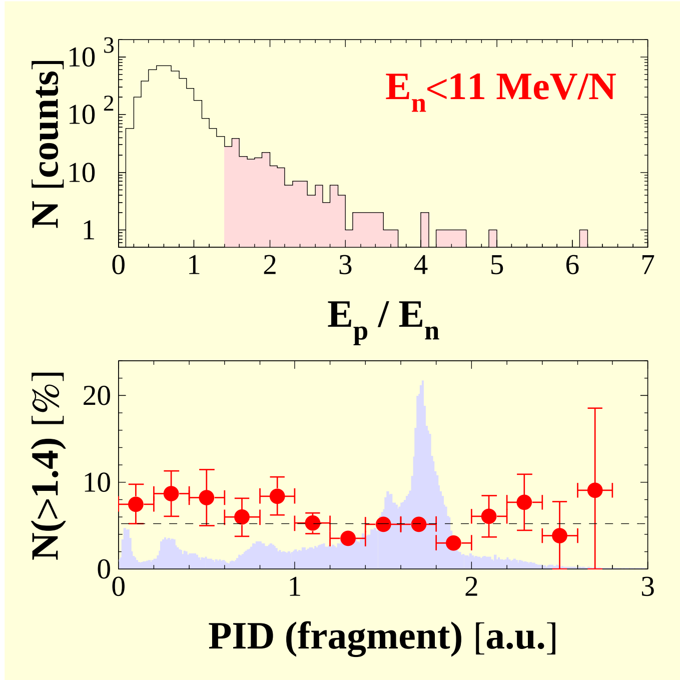
▶ light output saturation :



▶ pulse-shape discrimination :



▶ low-energy background :



▷ low (& flat) rate !

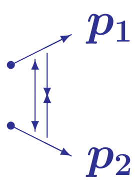
▶ bck evts : $({}^{14}\mathrm{Be}, {}^{12}\mathrm{Be} + n)$ $[{}^{2}\mathrm{n}]$

▷ lower limit on E_n [11–18]

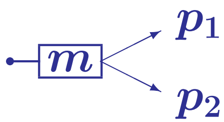
interpret the correlation factor

$x \leftrightarrow x$

bosons or fermions



FSI



resonances

$$C(p_1,p_2) \;=\; 1 \;+\; \underbrace{\langle b_0(q,p)\rangle}_{B_0 \equiv \mathrm{QSS}} \;+\; \underbrace{\langle b_i(q,p)\rangle}_{B_i \equiv \mathrm{FSI}}$$

$$\begin{aligned}
x &= x_1 - x_2 \;=\; (r_1,t_1) - (r_2,t_2) \\
B_0 &= -\frac{1}{2}\langle \cos(qx)\rangle \;=\; -\frac{1}{2}\int W(x)\,\cos(qx)\,d^4x \\
B_i &= \frac{1}{2}\left\{|f(k^\star)|^2\langle|\phi_{p_1p_2}(x)|^2\rangle + 2\,\Re\Big[f(k^\star)\langle\phi_{p_1p_2}(x)\cos(qx/2)\rangle\Big]\right\} \\
&= \int 2\pi\, r_T\, dr_T\, dr_L\, dt\, W(x)\,\Big\{|f(k^\star)\phi_{p_1p_2}(x)|^2 + \\
&\quad 2\,\Re[f(k^\star)\phi_{p_1p_2}(x)]\, J_0(q_T r_T/2)\cos[q_0(r_L - vt)/2v]\Big\}
\end{aligned}$$

$$\left.\begin{aligned} t &= 0 \\ W(x_i) &= e^{-r_i^2/2r_0^2} \\ W(x) &= e^{-r^2/4{r_0}^2} \end{aligned}\right\} \xrightarrow{\star} \begin{aligned} C(q) \;\approx\; & 1 - \tfrac{1}{2}\exp(-q^2 r_0^2) \\ & + \tfrac{|f|^2}{4r_0^2}\left(1 - \tfrac{d_0}{2\sqrt{\pi}r_0}\right) + \tfrac{\Re f}{\sqrt{\pi}r_0}F_1(qr_0) - \tfrac{\Im f}{2r_0}F_2(qr_0) \end{aligned}$$

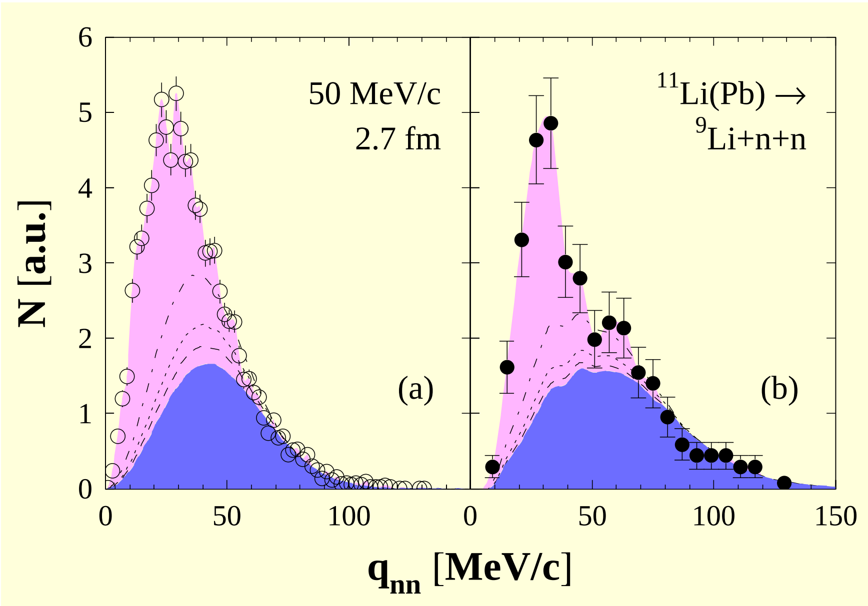
* R. Lednicky and V.L. Lyuboshits, Sov. J. Nucl. Phys. 35 (1982) 770

how to iterate

▶ calculate $\langle C \rangle$ for each neutron :

$$\langle C \rangle(p) = \int C(p,k)\,\frac{d\sigma}{dk}\,dk = \int C(p,k)\,\frac{d\tilde{\sigma}/dk}{\langle C \rangle(k)}\,dk$$

▷ subtle, but essential detail !



▶ in practice : N neutrons measured ...

$$\langle C \rangle^{(n)}(p_i) = \frac{1}{N-1}\sum_{\substack{j=1\\ j\neq i}}^{N} \frac{C^{(n-1)}(p_i,p_j)}{\langle C \rangle^{(n)}(p_j)}$$

▷ no need to normalize !

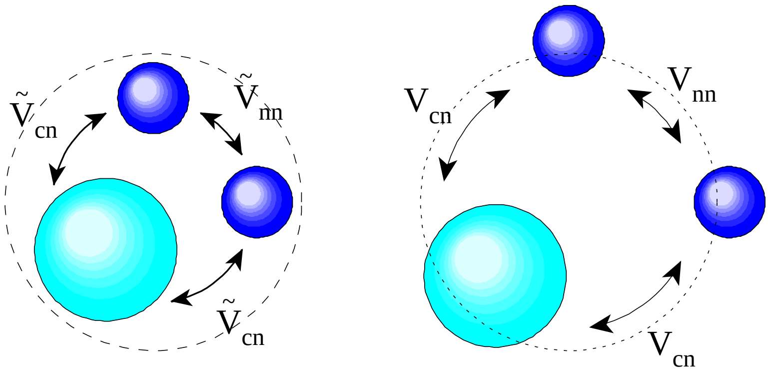
▷ $C^{(n-1)}(p_i,p_j) \approx C^{(n-1)}(|\vec{p}_i - \vec{p}_j|)$ ...

▷ interpolate around q_{ij} !

▷ effect easily simulated !!!

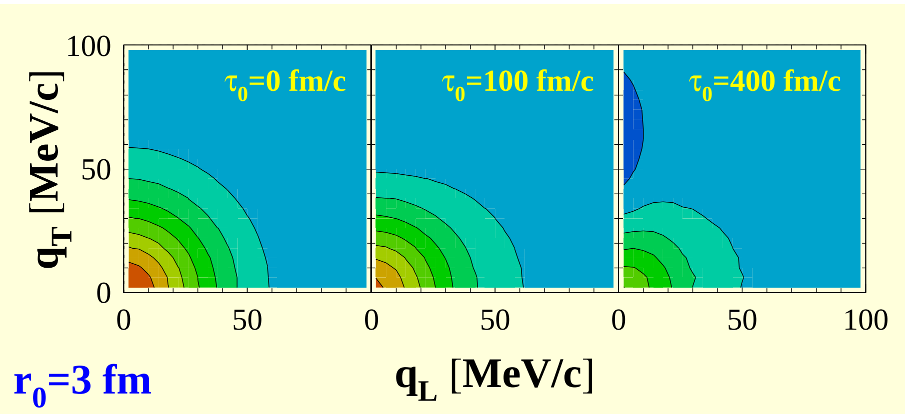
multiple correlations ($N > 2$)

▶ it is a 3-body problem ...:

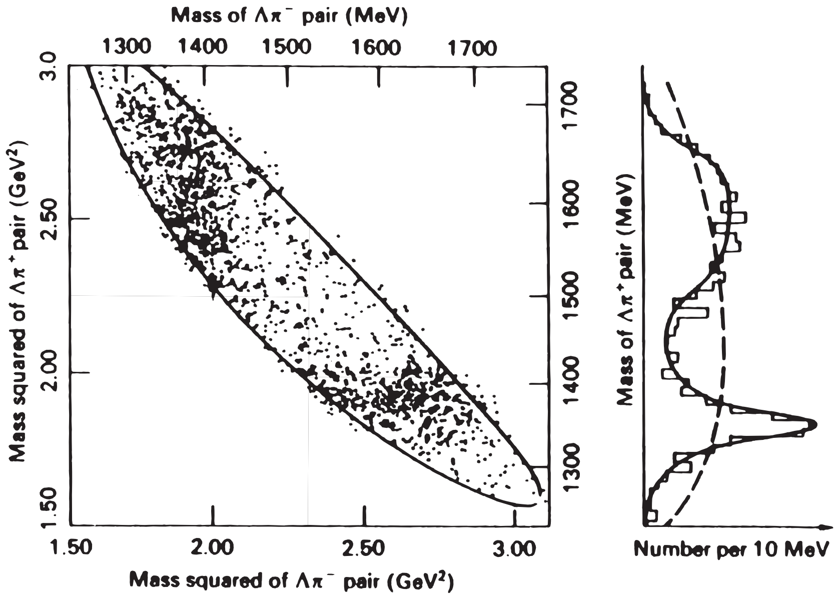


(a) (b)

▷ what is the effect of V_{cn} ?



▶ multiple correlations
in particle physics : Dalitz plots



▷ define "normalized" masses :

$$m_{ij}^2 = \frac{M_{ij}^2 - (m_i + m_j)^2}{(m_i + m_j + E_d)^2 - (m_i + m_j)^2}$$

MUST setup : "hyperheavy" hydrogen ?