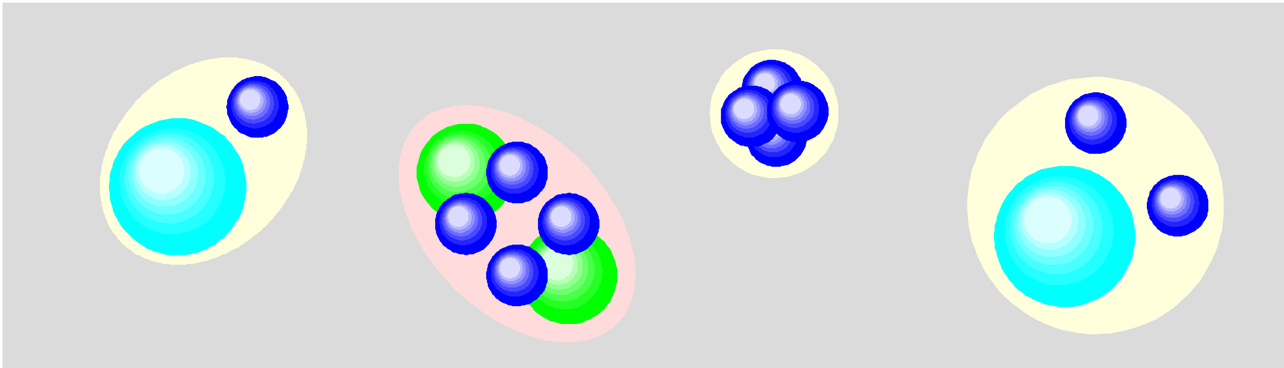
European Summer University

The Secrets of the Atomic Nucleus

Strasbourg, 28 June - 4 July 2009

"Exotic Nuclear Matter: Clusters and Halos in Nuclei"



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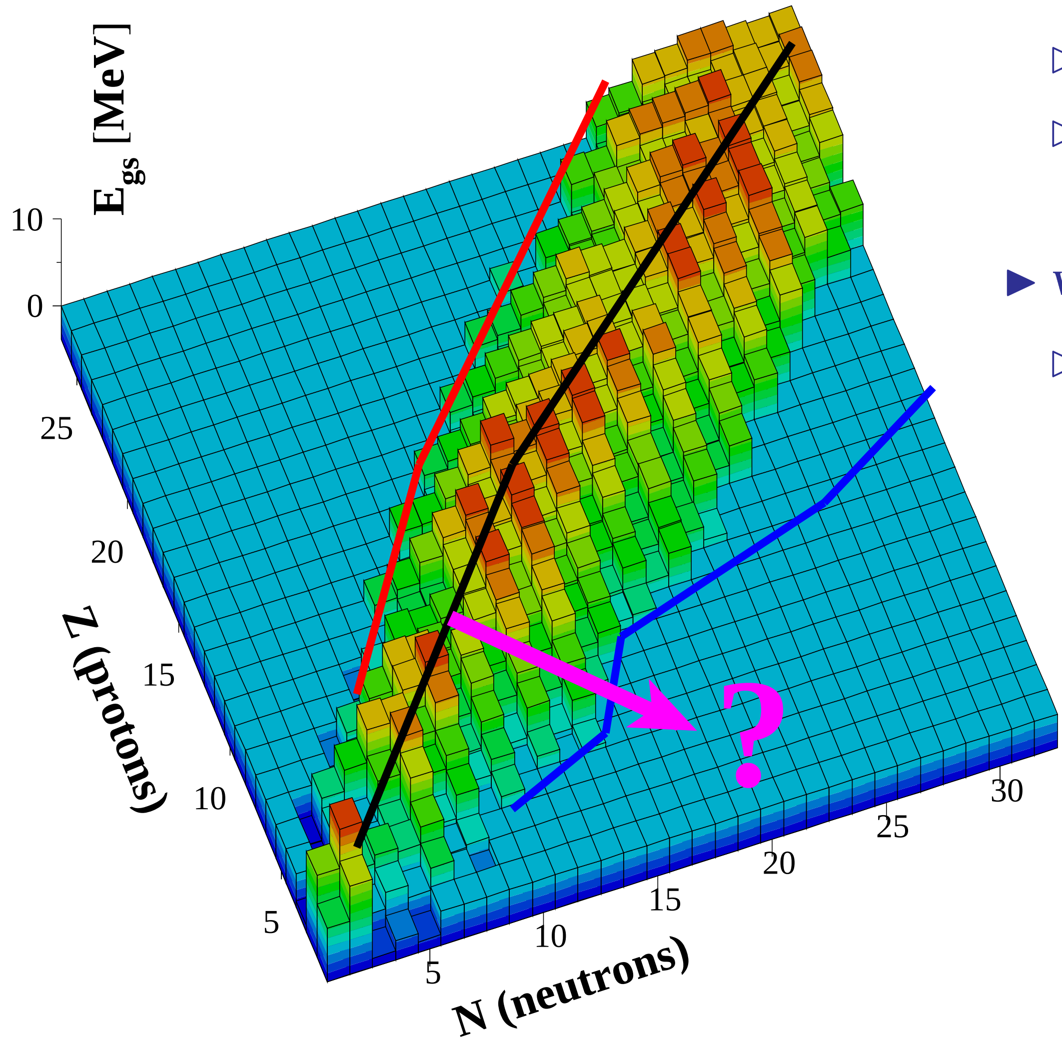
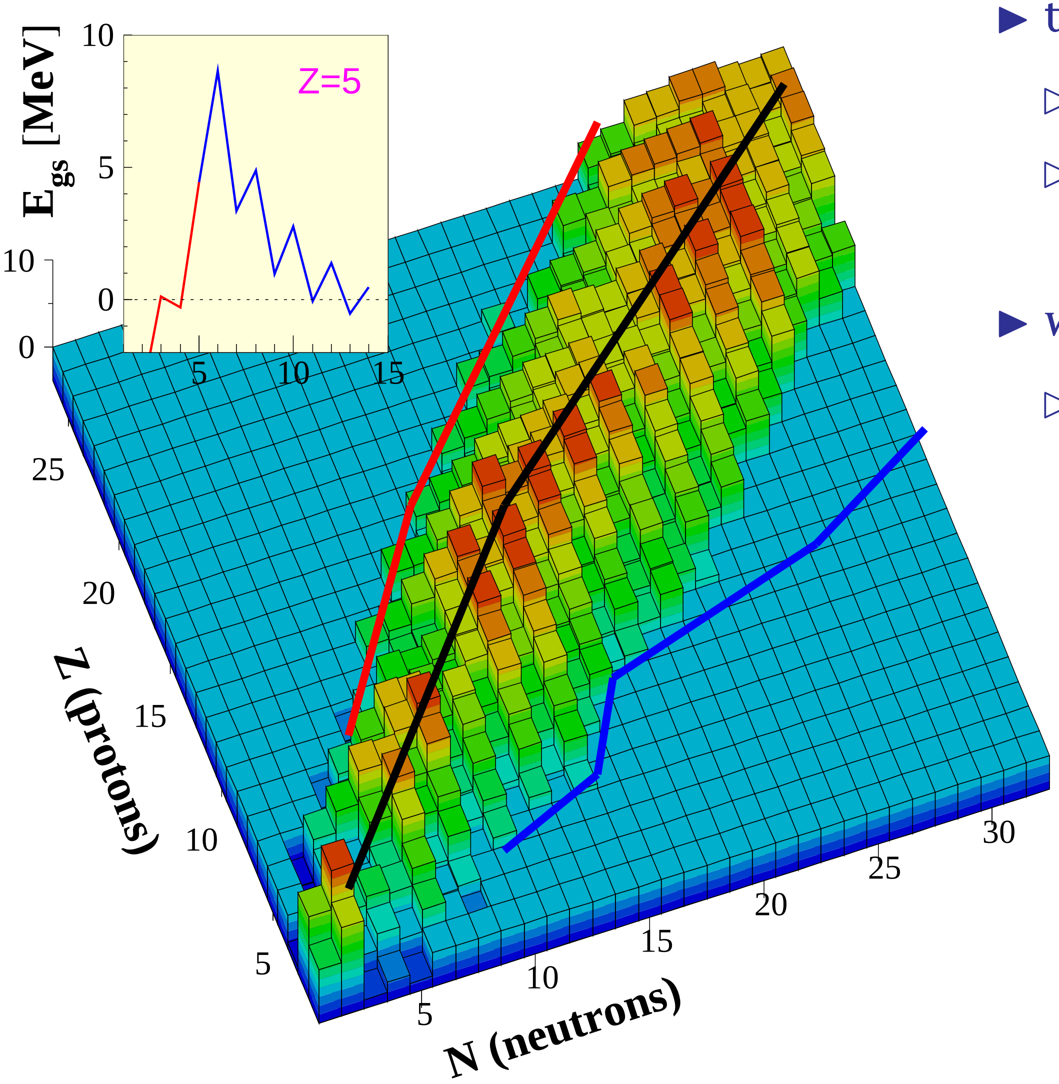
Neutrons & protons in nuclei



- the valley of stability :
  - $B = Nm_n + Zm_p - M(N,Z)$
  - rather a ridge of stability …
- where are the drip lines ?
  - $E_{gs}(N,Z)$
    $= \min\left[\sum M(n_i,z_i)\right] - M(N,Z)$
- very light nuclei :
  - access to extreme (N,Z) !!!

Neutrons & protons in nuclei



▶ the valley of stability :

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▶ where are the drip lines ?

▷ $E_{gs}(N, Z)$

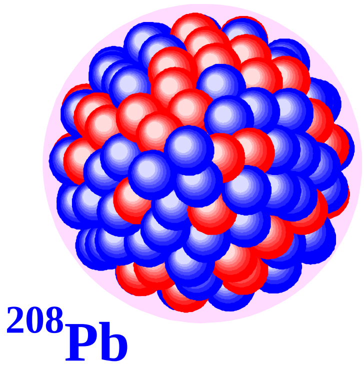
$$= \min\left[\sum M(n_i, z_i)\right] - M(N, Z)$$

▶ very light nuclei :

▷ access to extreme (N, Z) !!!

The liquid drop picture

- are nuclei liquid drops ?



- ▷ constant density
- ▷ short-range forces
- ▷ saturation
- ▷ deformability
- ▷ well defined surface (tension)
- ▷ mean free path + size…
- ▷ yes, but quantum liquid

The liquid drop picture

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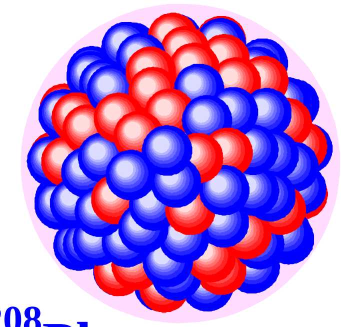


^{208}Pb

▷ constant density

▷ short-range forces

▷ saturation

▷ deformability

▷ well defined surface (tension)

▷ mean free path + size...

▷ yes, but quantum liquid

▶ semi-empirical mass formula :

$$M(N,Z) = N m_n + Z m_p - B(N,Z)$$

$a_v\, A$	volume
$-\, a_s\, A^{2/3}$	surface
$-\, a_c\, Z^2/A^{1/3}$	Coulomb
▷ $-\, a_a\, (N-Z)^2/A$	asymmetry
$\pm\, \delta/A^{1/2}$	pairing

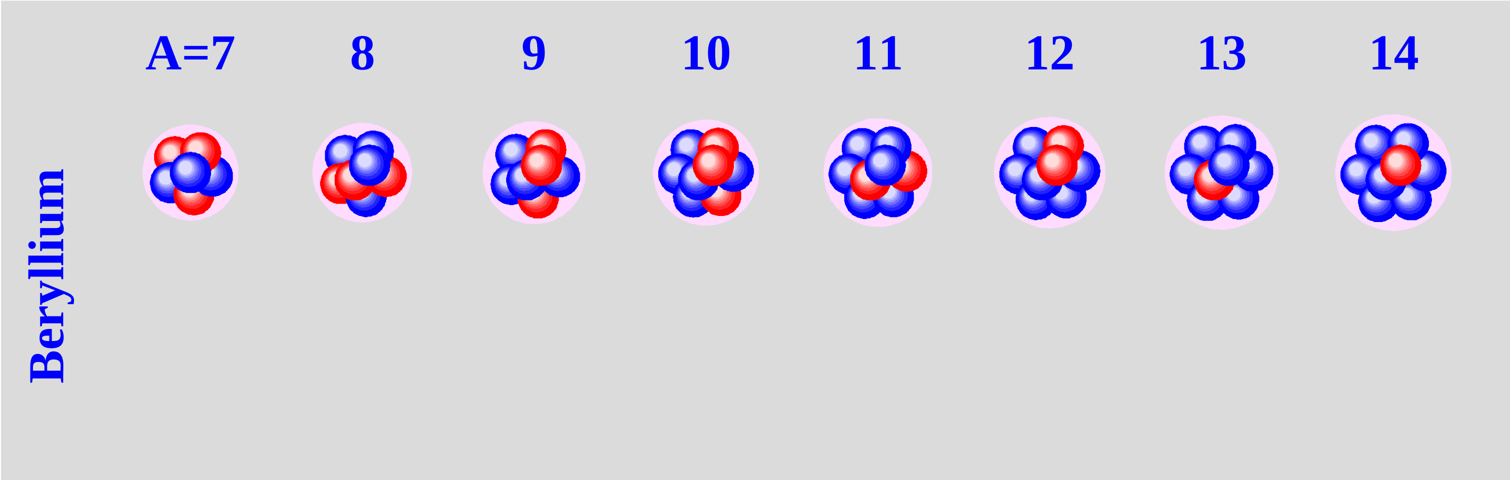
...and so the nucleus "behaves" as if :

▷ limits were sharp $[R \sim r_0 A^{1/3}]$

▷ volume was uniform $[\rho(r) \sim \rho_0]$

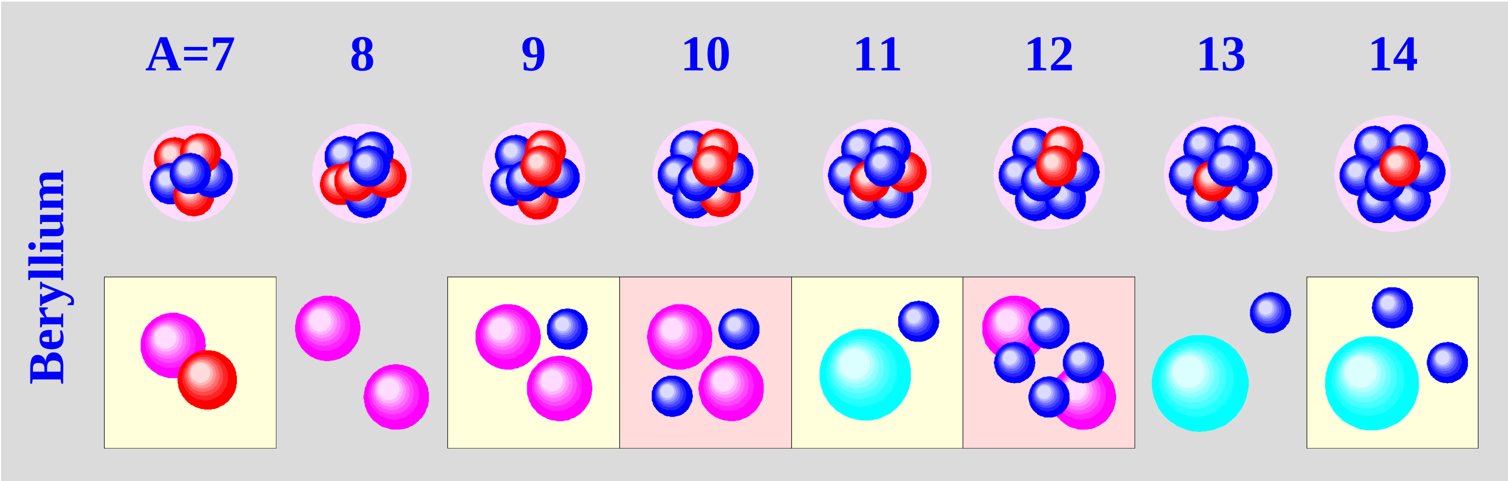
▷ and homogeneous $[\rho_n \approx \frac{N}{Z}\rho_p]$

A complete isotopic chain



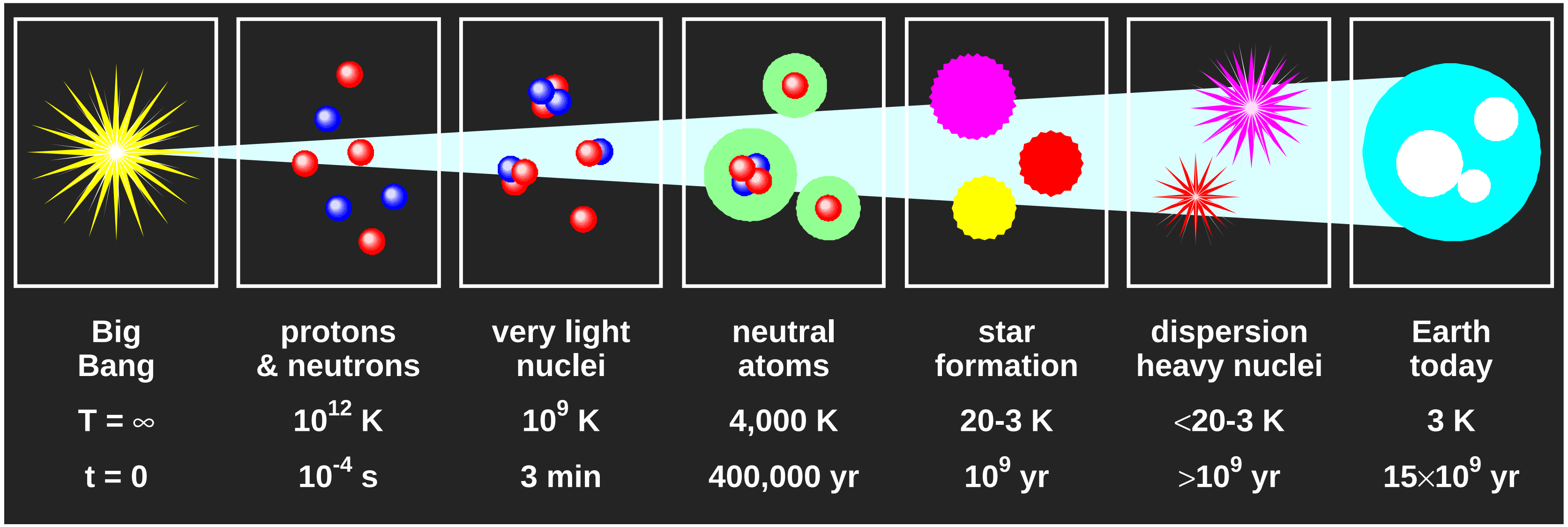
▶ "normal" size increase : $R = r_0\, A^{1/3}$?

A complete isotopic chain



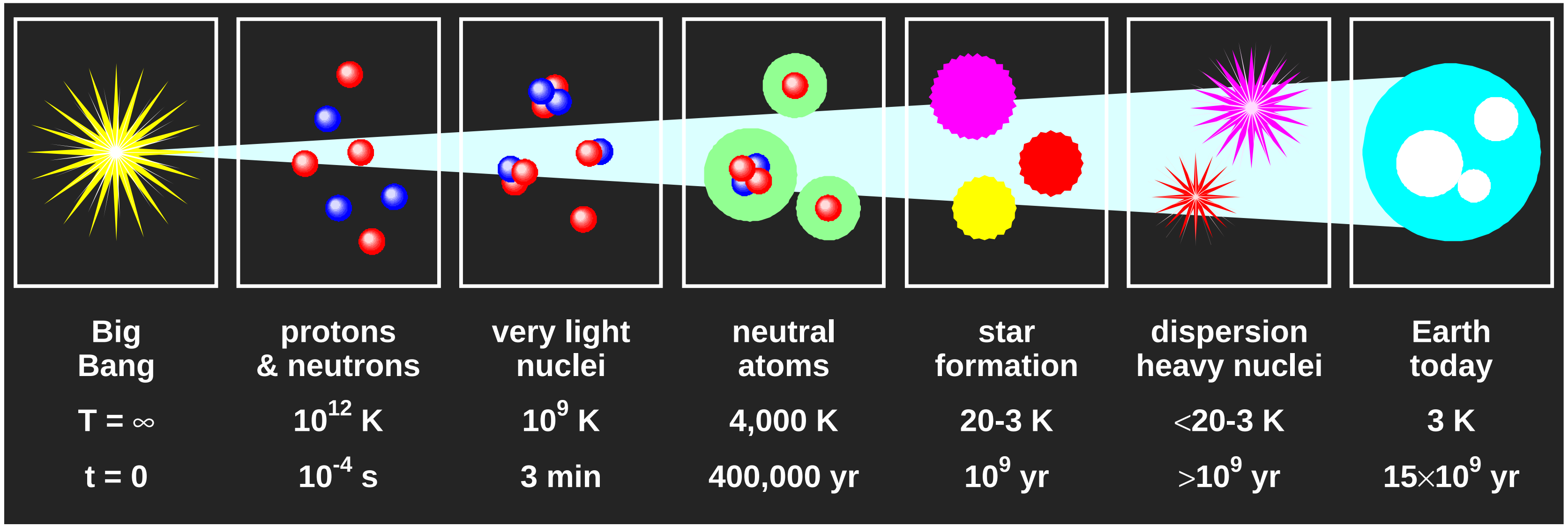
- many (all?) extreme configurations :
  - clustering
  - unbound resonant states
  - nuclear molecules
  - neutron haloes
  - borromean systems
  - neutral nuclei ?

Expansion of the Universe



- ▶ nucleosynthesis :
  - ▷ why [and how] few (N, Z) ?
  - ▷ do unknown combinations exist ?
  - ▷ why two steps ?

Expansion of the Universe



- nucleosynthesis :
  - ▷ why [and how] few (N, Z) ?
  - ▷ do unknown combinations exist ?
  - ▷ why two steps ?
- on Earth only "normal" nuclei left :
  - ▷ study exotic nuclei in laboratory !

Extraterrestial nuclei on Earth

- ▶ $^{19}C \longrightarrow {}^{18}C + n$ experiment @ GANIL :
  - ▷ add $7n$ to ^{12}C ?? study it in less than 49 ms ???

Extraterrestial nuclei on Earth

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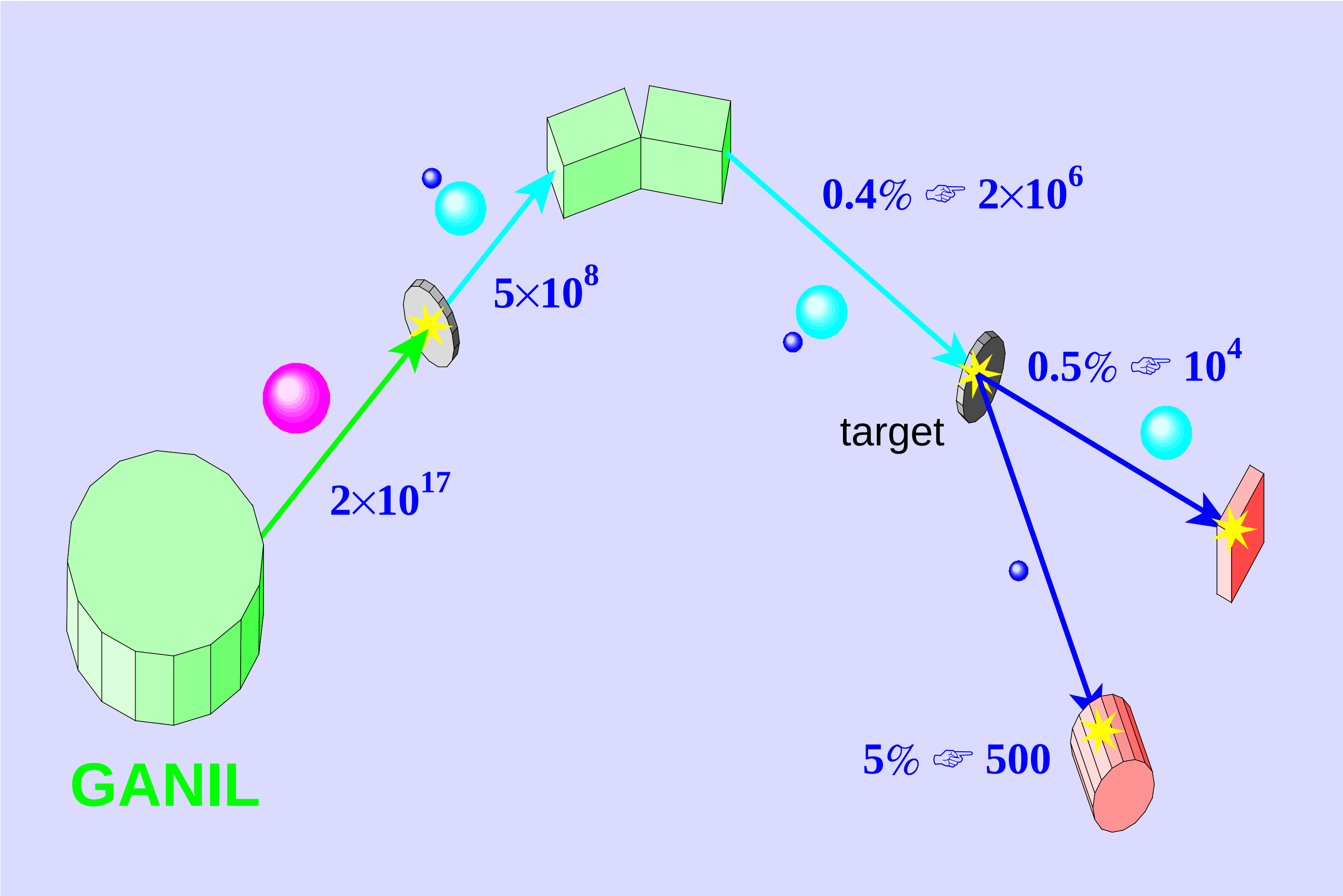
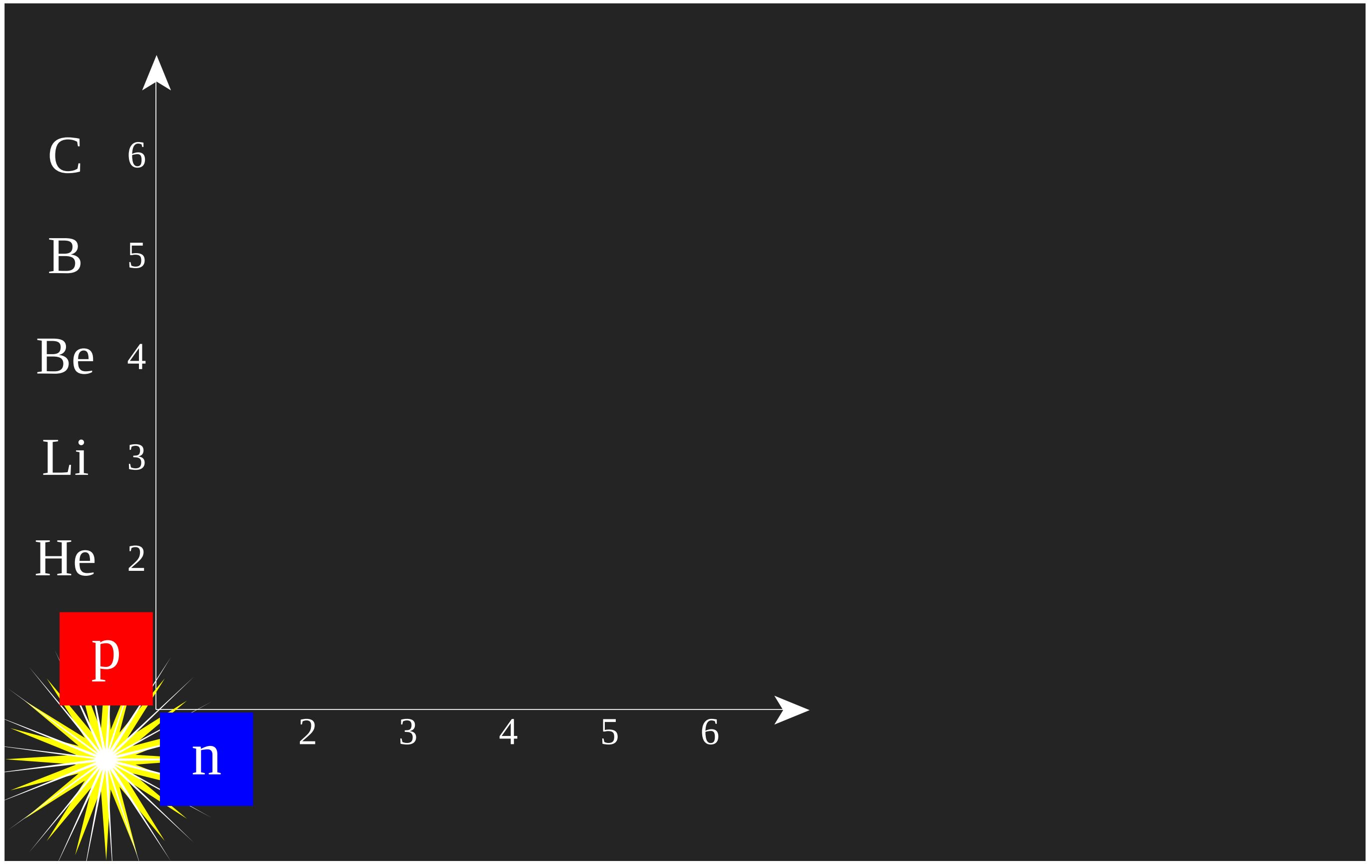


Nuclei in the nucleus



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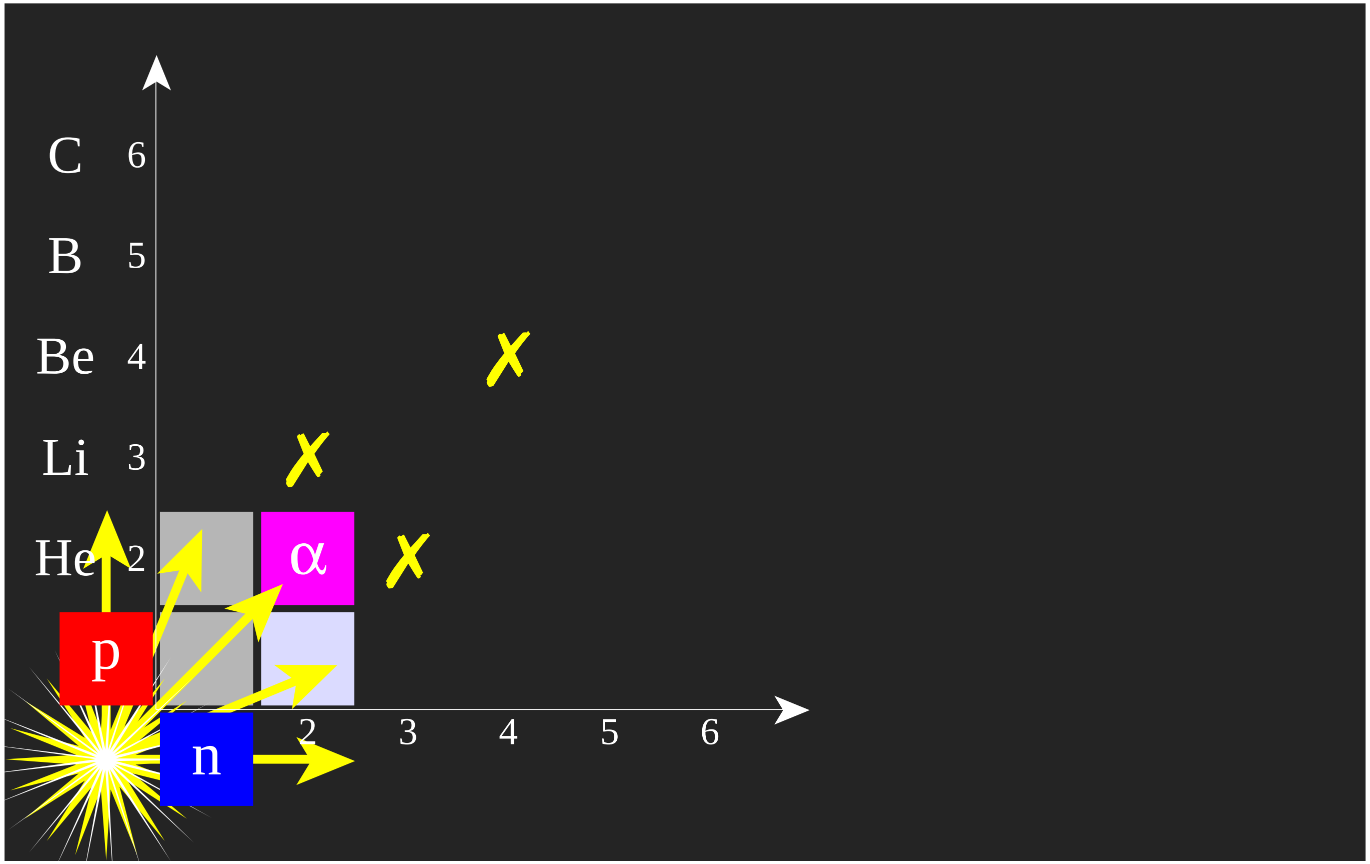

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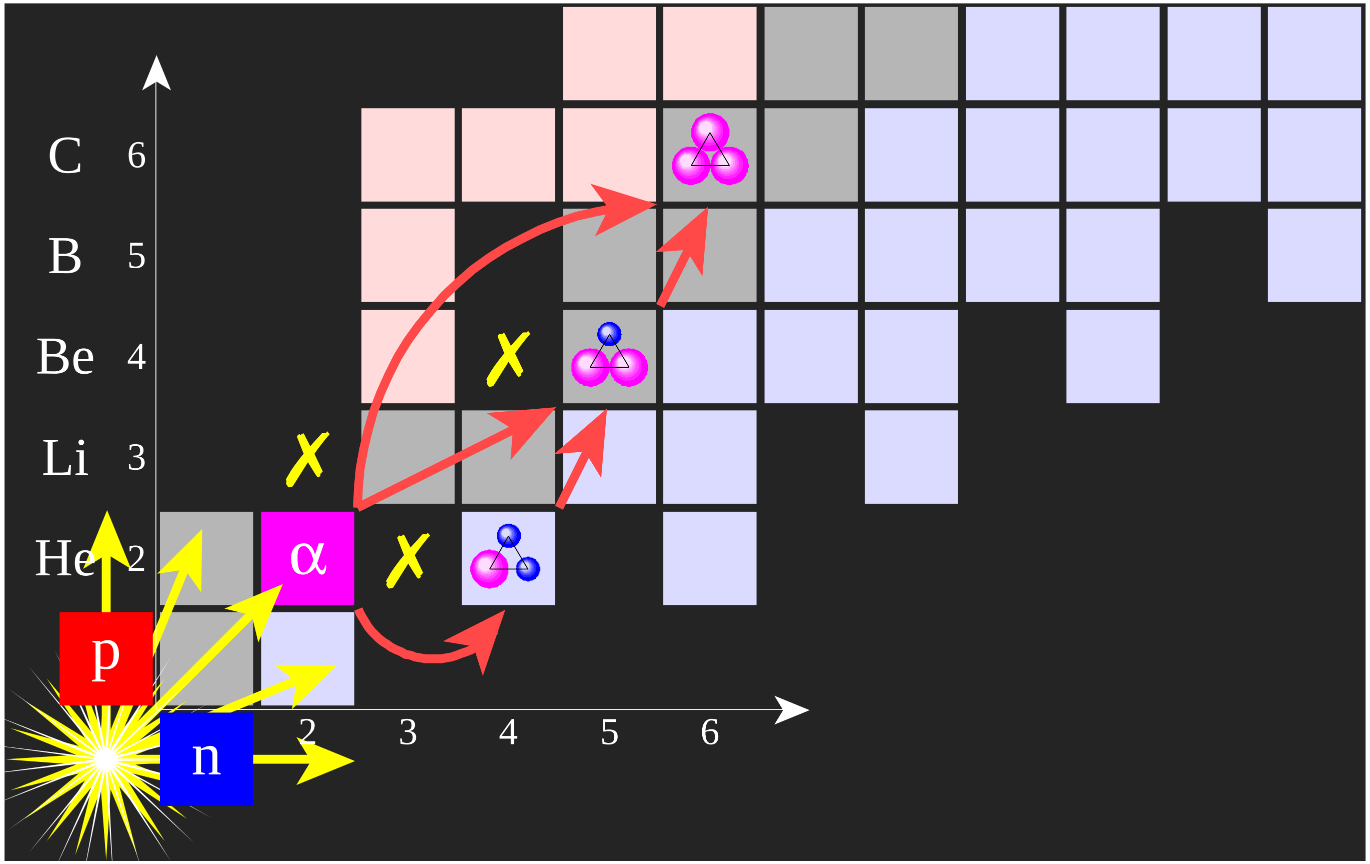

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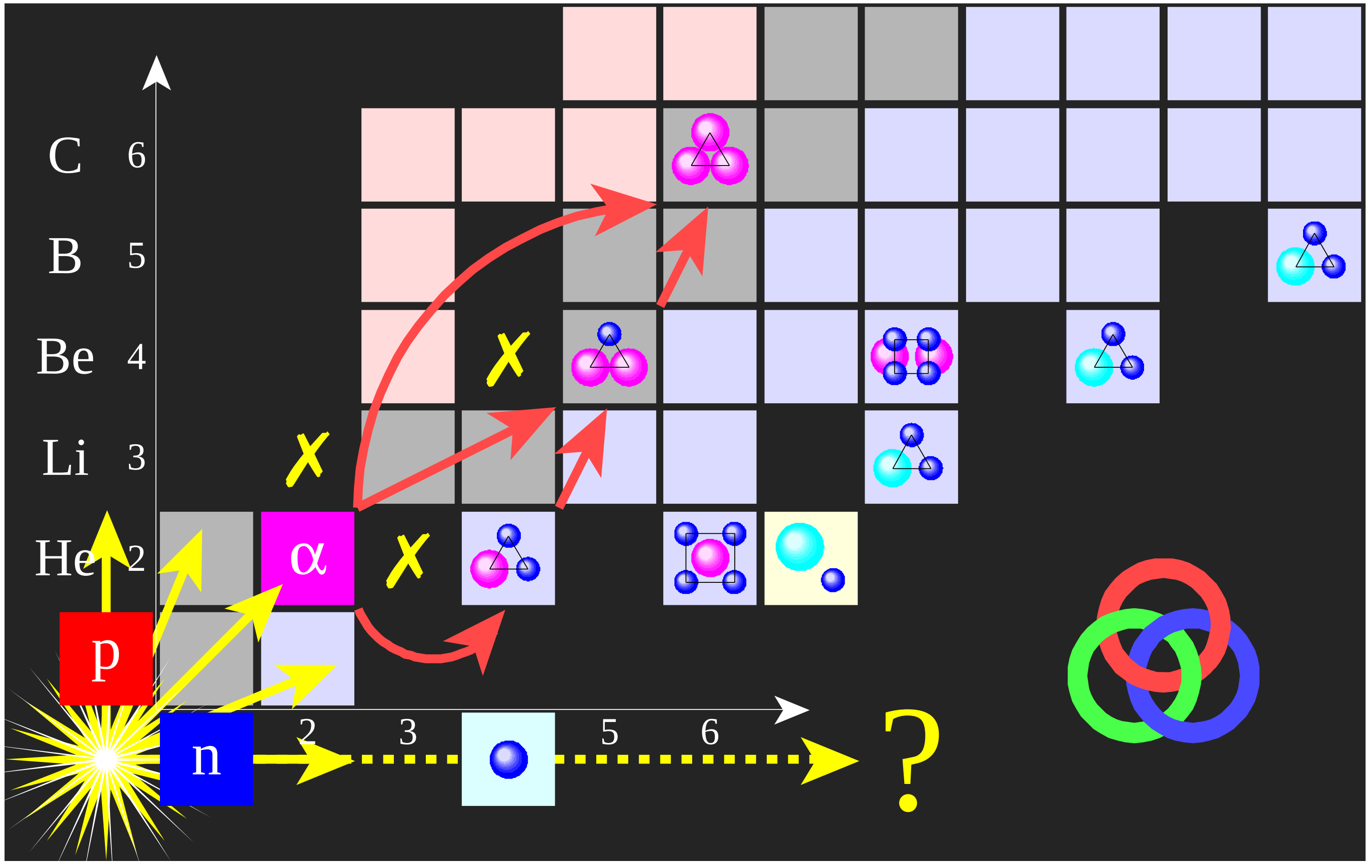


▷ N nucleons ≡ few (correlated) clusters !

▷ formation of carbon (and $A > 12$)

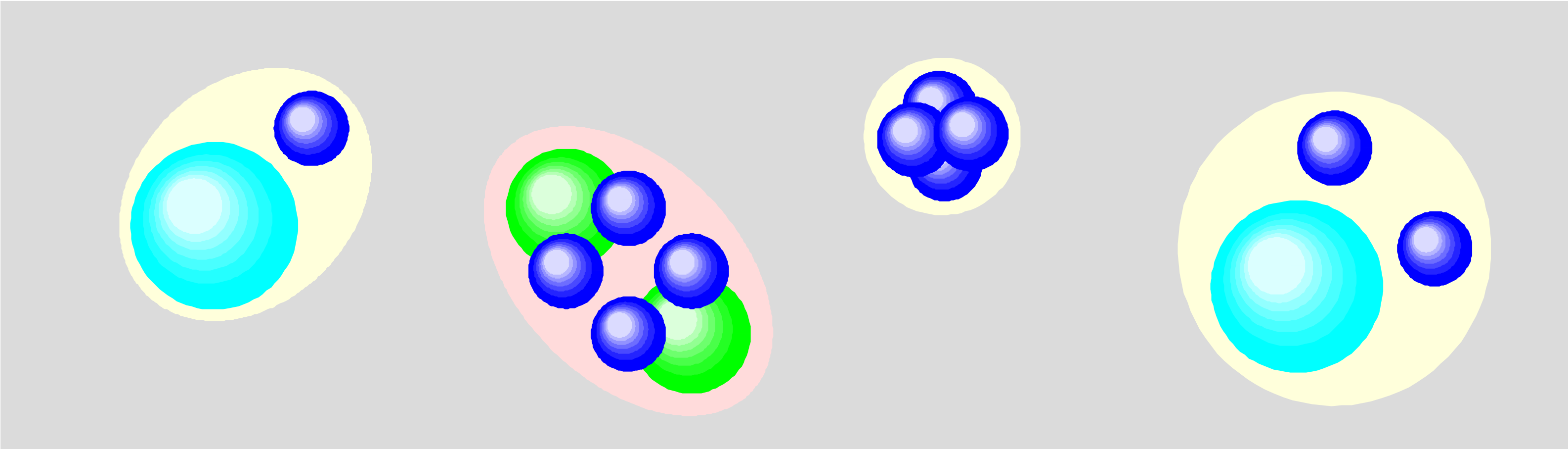
▷ are nuclei sharp/uniform/homogeneous ???

Exotic exotic nuclei (I)

(I) The Nuclear Halo

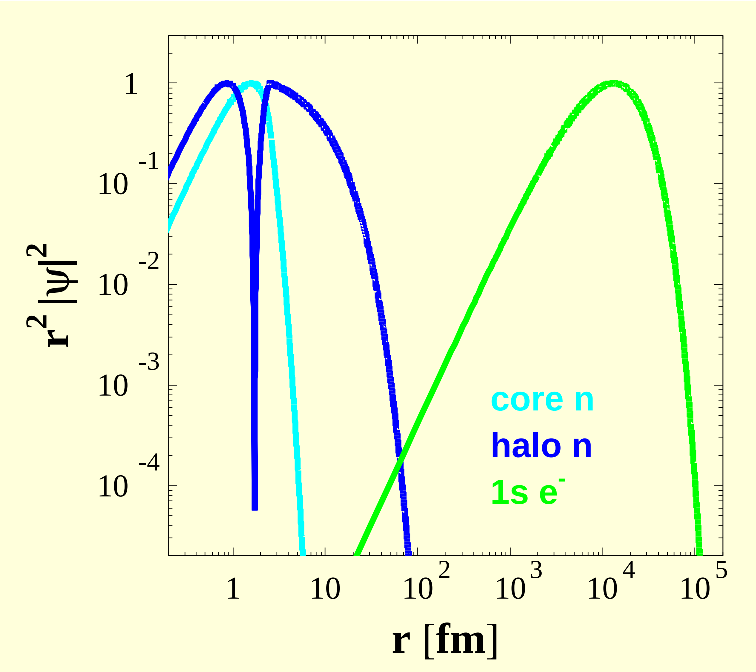
(II) Nuclear Molecules

(III) Neutron Clusters ?



Halo : an exaggerated picture ?

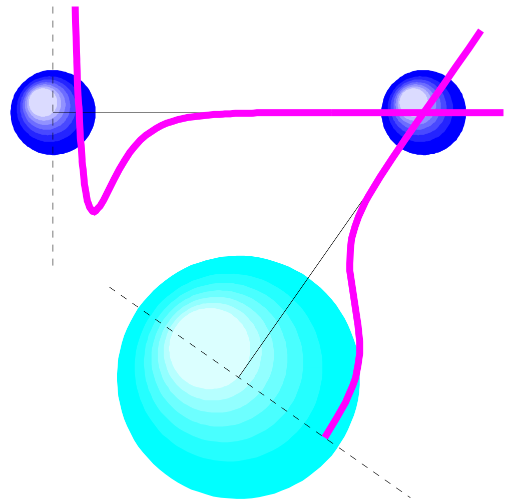
▶ the size of the halo [Be atom] :



▷ still negligible at atomic level . . .

▷ a potentially huge nuclear effect !
[. . .and theoretical problem!]

▶ the geometry of the halo [^{11}Li] :



▷ rms distances ≫ binary ranges !

▷ classically forbidden configurations

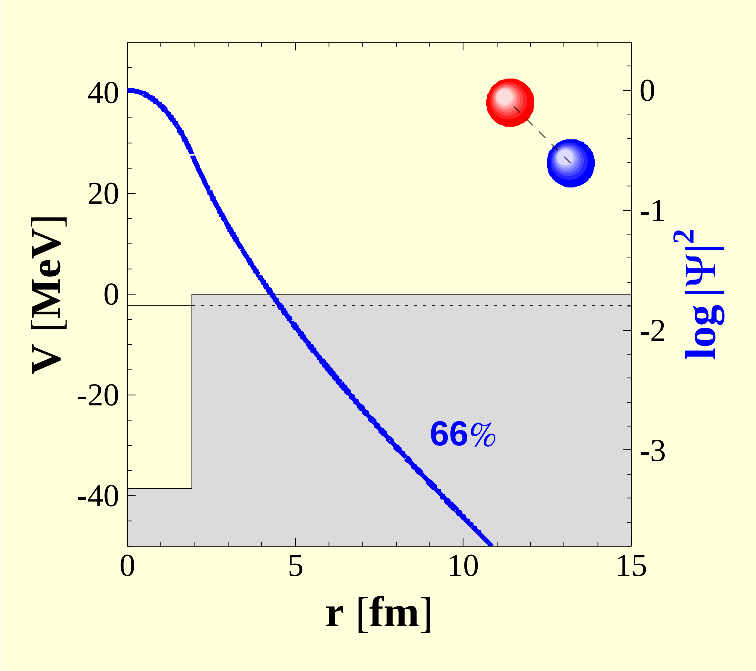
▶ Ö picture : not exaggerated at all !!!

A quantum liquid

- particle-wave duality :
  - ▷ wavelength ∼ nuclear radius
- the nucleon wave function :

$$H|\Psi\rangle = E|\Psi\rangle$$

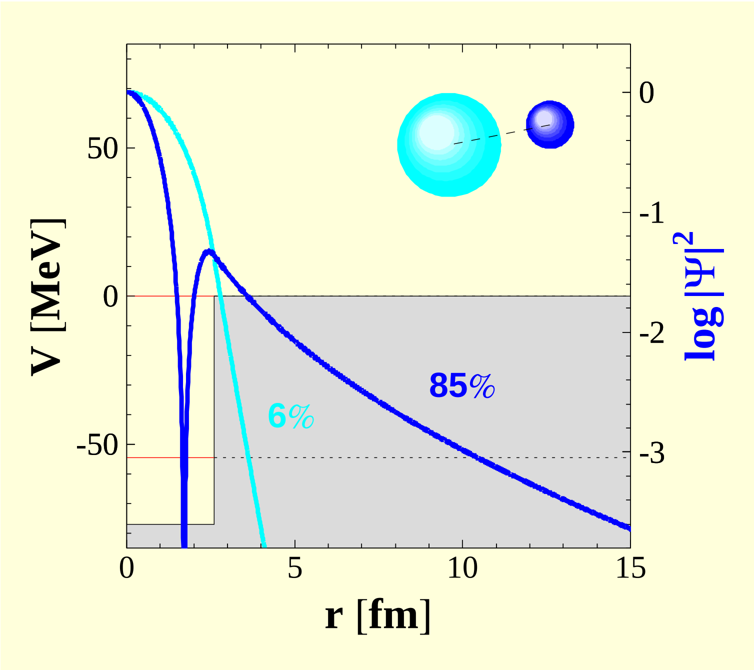
  - ▷ Ψ vanishes outside the nucleus
  - ▷ but $|\Psi|^2 \neq 0$ for being outside …
- the simplest case : $\ell = 0$ neutron
  - ▷ no Coulomb barrier $[Z/r]$
  - ▷ no centrifugal barrier $[\ell(\ell+1)/r^2]$
  - ▷ "only" the nuclear potential …
- the deuteron $[B(n) = 2.2$ MeV$]$:



- very n-rich nuclei ? $[B(n) \rightarrow 0]$

The neutron(s) halo

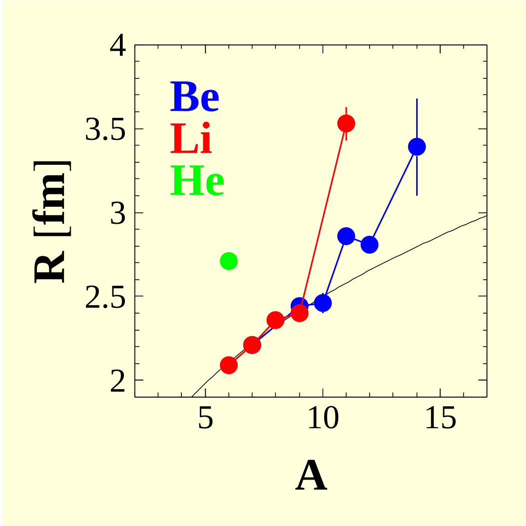
▶ neutron ($\ell = 0$) in $A = 10$ nucleus :



▷ very big nuclei !!!

▷ two phases : (core)+halo …

▶ interaction cross-sections [$\propto \pi R^2$] :



▷ ^{11}Li $\equiv$ ^{48}Ca … but : $2n \equiv {}^{208}$Pb !!!

▶ when two neutrons in the halo :

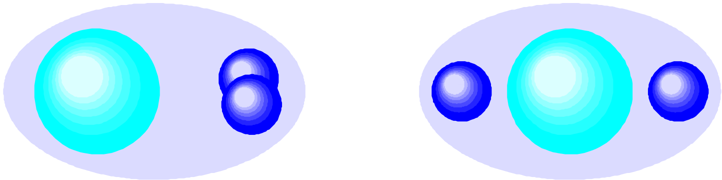
▷ first seen as core-dineutron

▷ but core-n-n correlations …

The structure of the neutron cloud

- nucleons at $\rho \neq \rho_0$!!!
  - a laboratory for N-N interaction

- how do they "move" [ ] ?



  - a step inside the halo …

- more subtle experiments ($\sigma\downarrow$) :
  - halo transfer [^{6}He + α]
  - proton capture [^{6}He + p]
  - or more subtle techniques …

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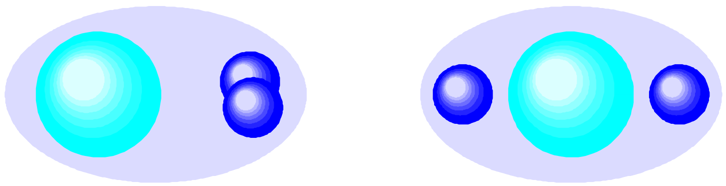

▷ a step inside the halo …

▶ more subtle experiments ($\sigma\downarrow$) :

▷ halo transfer [^{6}He + α]

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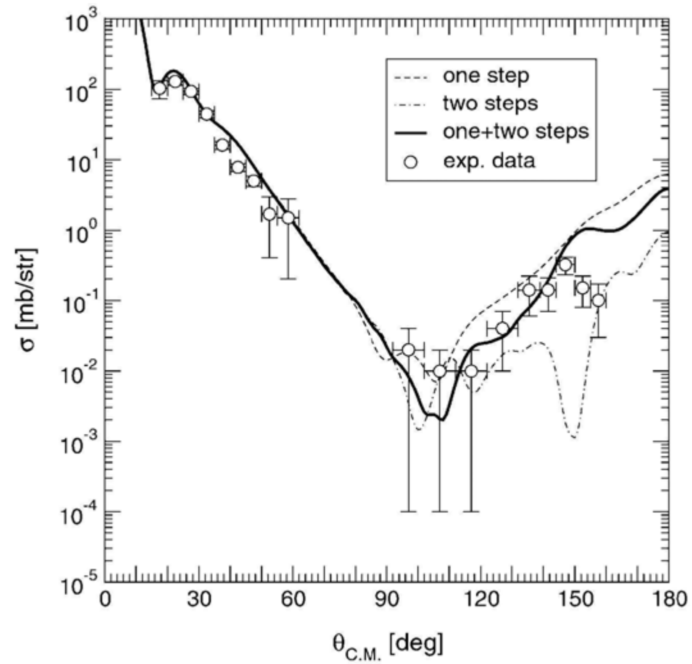
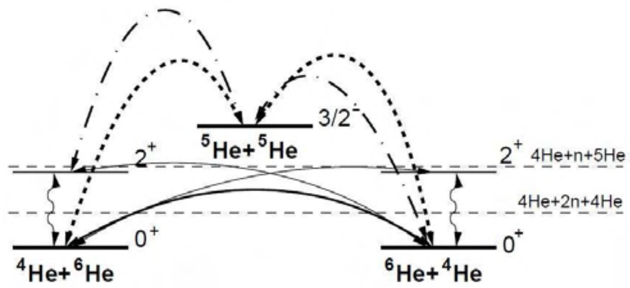
▷ or more subtle techniques …

▶ halo transfer : α (^{6}He, α) ^{6}He



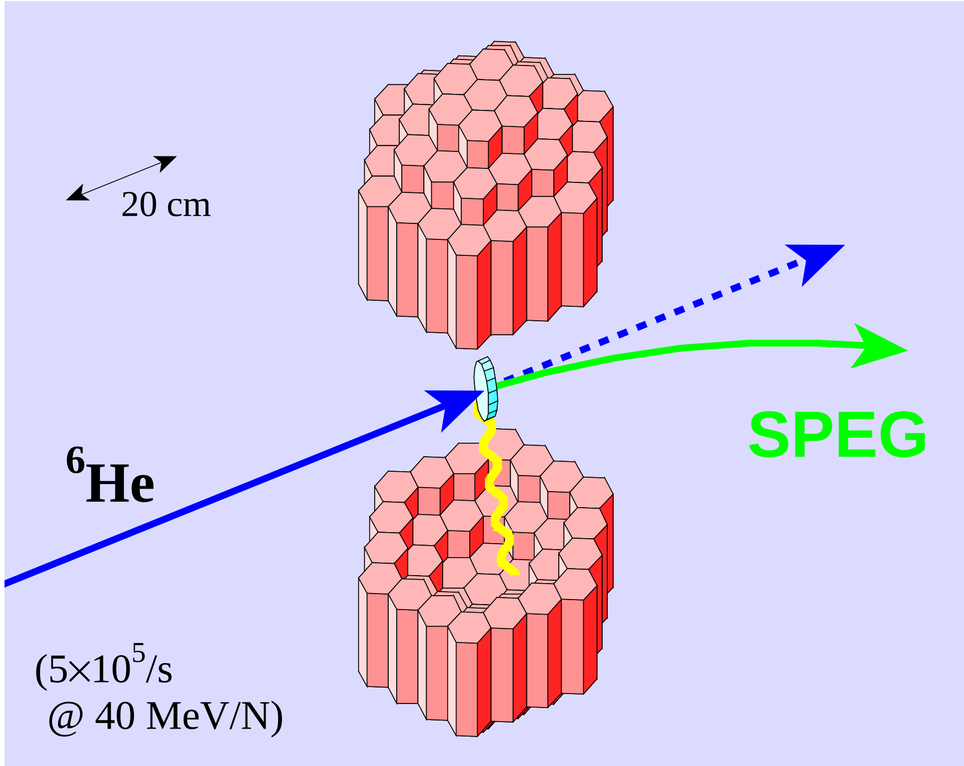
▷ dineutron configuration ! (?)

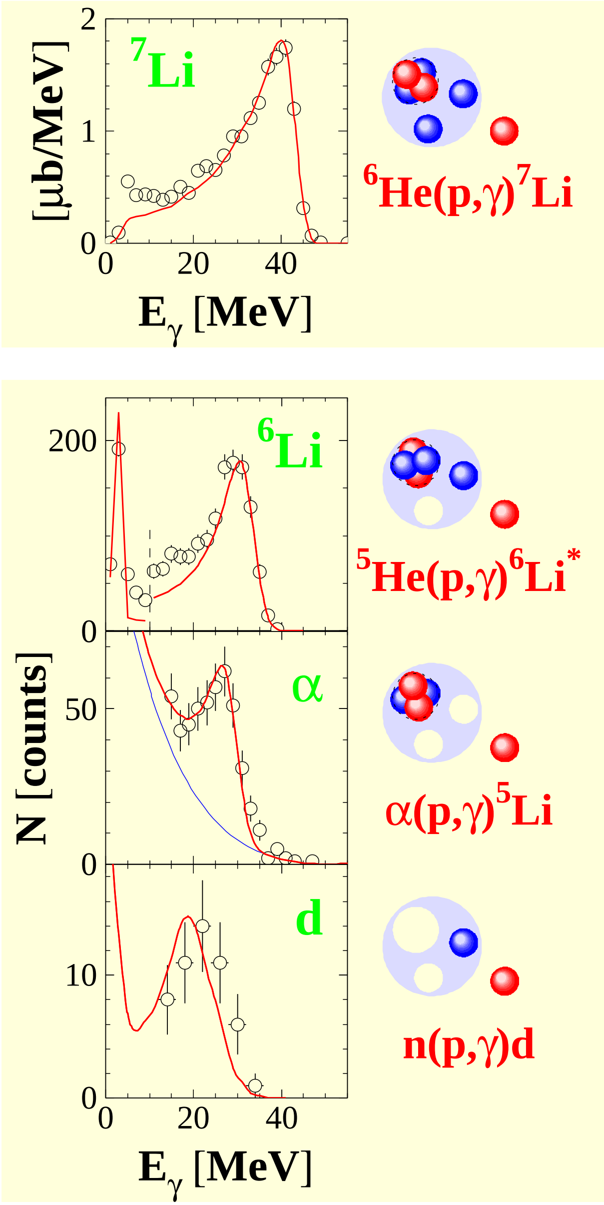
▷ assumption : one-step process…



Radiative capture

▶ proton capture on clusters: ^{6}He (p, γ) X





▷ a reference: capture on ^{6}He

▷ several quasi-free captures !!!

▷ no $[2n\ (p, \gamma)\ t]$ and $[t\ (p, \gamma)\ \alpha]$ events…

▷ dominant α-n-n configuration !

The n-n interaction

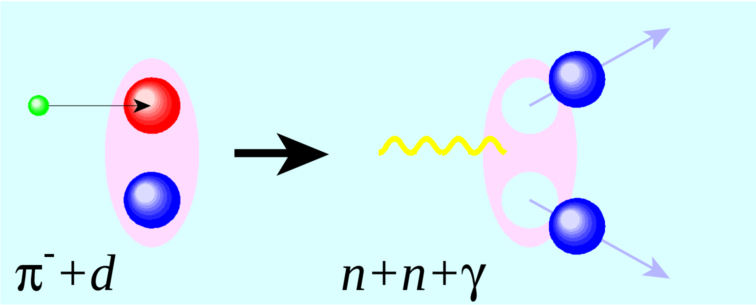
- low energy N-N interaction :

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

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

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

- neutron-neutron "collisions" ?



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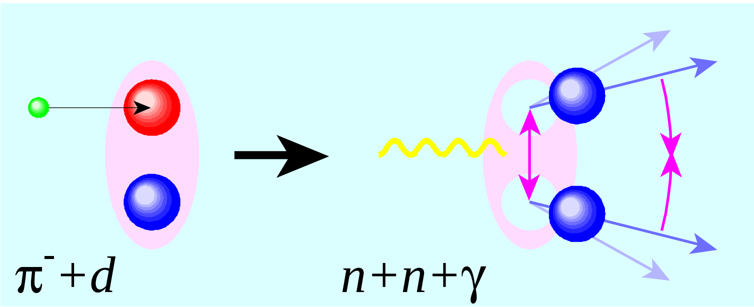


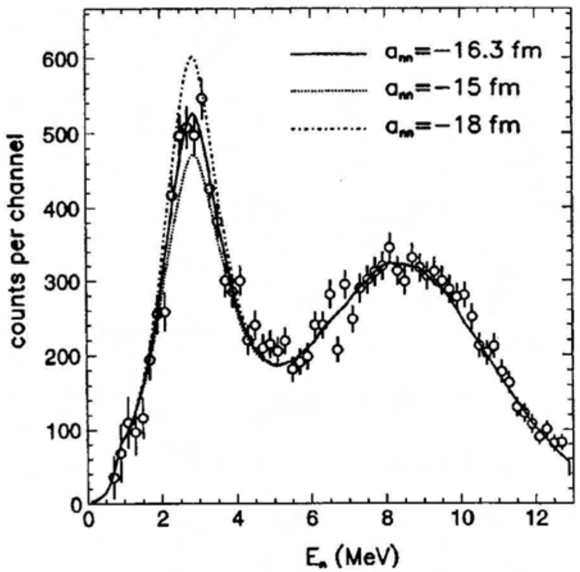
▷ final state modified by V_{nn} !

▶ how is it modified ?

▷ by the n-n distance

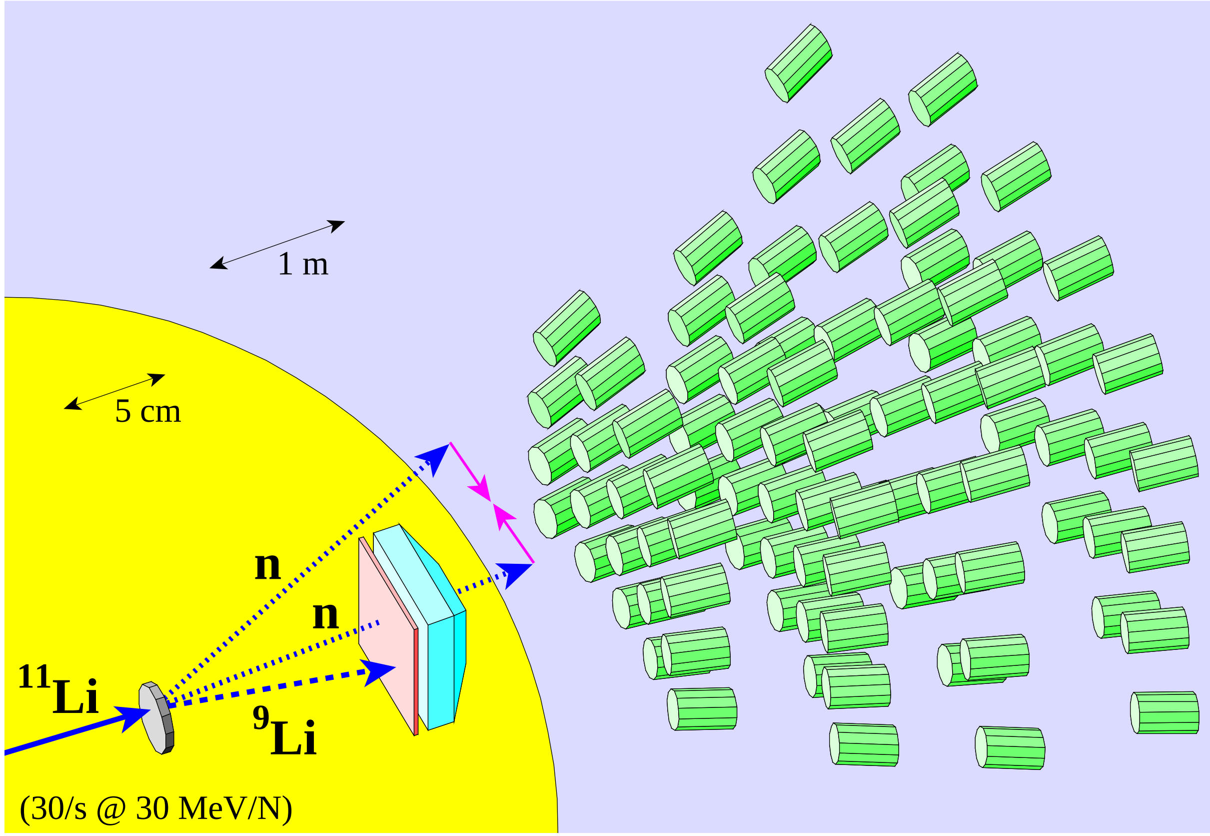
▷ by the n-n interaction

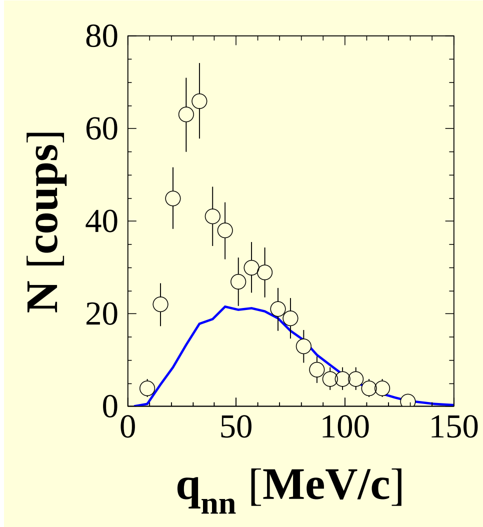
$$\sigma(q) \approx \Omega(q) \times \left| \int \psi_d\, \psi_s^*(a_{nn})\, d^3r \right|^2$$
$$\approx \Omega(q) \times \frac{1}{1 + q^2\, {a_{nn}}^2}$$



The neutron femtoscope

▶ the halo of ^{11}Li : ö ↔ ⊛ ?





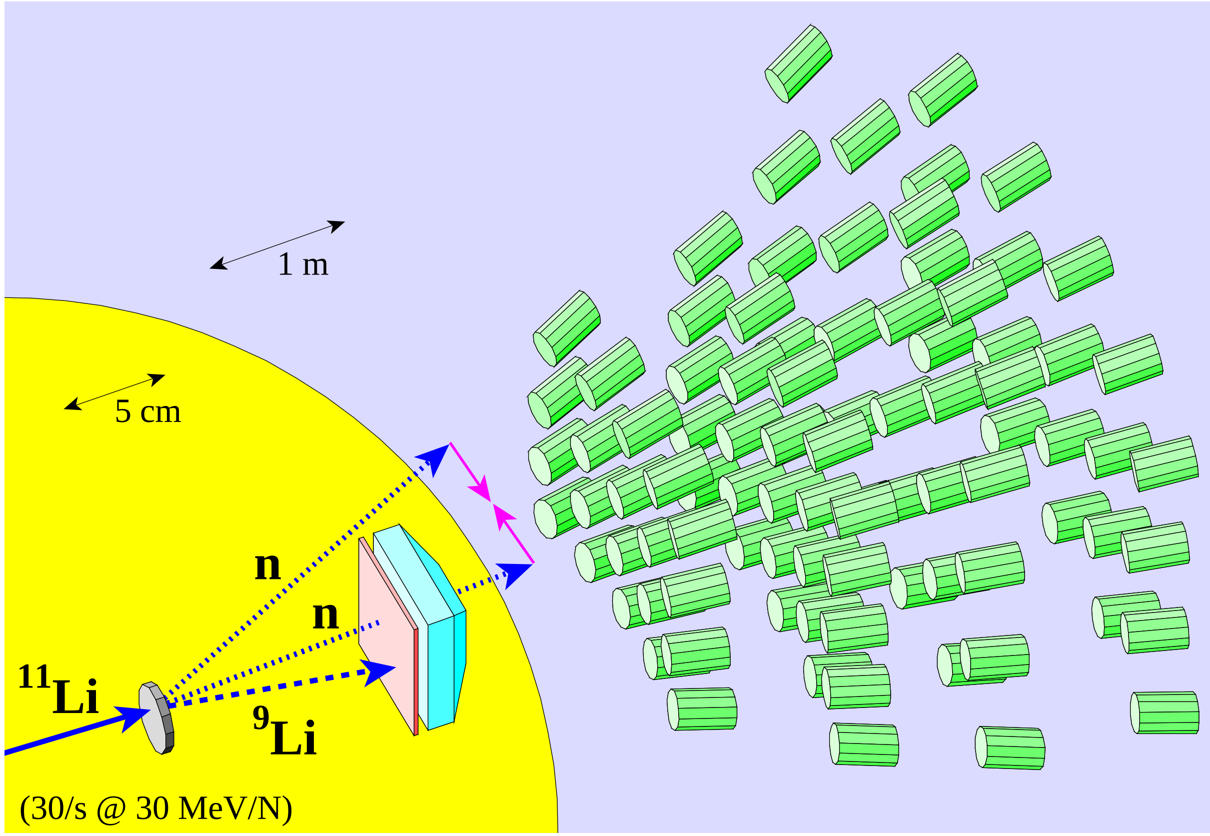
▷ $\sigma(q) \equiv \Omega(q) \times C_{nn}\,\{\psi(r_{nn}), a_{nn}\}$:

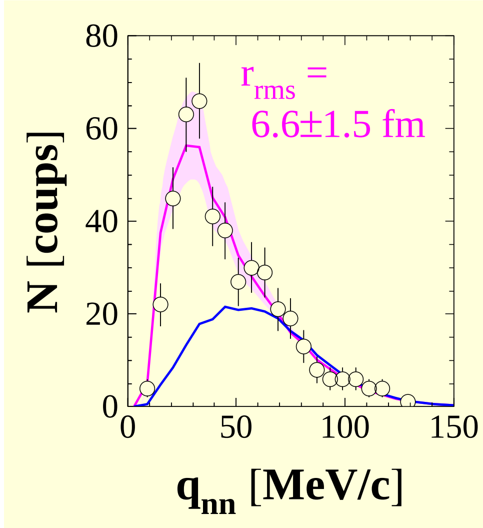
⇝ $\sigma(q)$ is measured

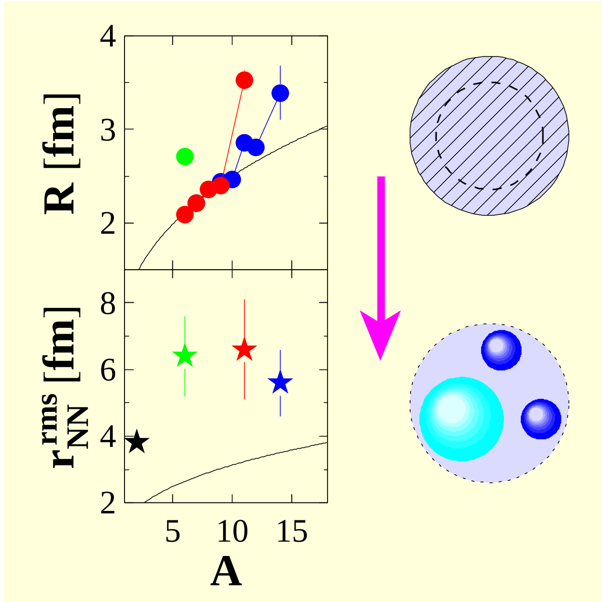
⇝ event mixing provides $\Omega(q)$ …

The neutron femtoscope

▶ the halo of ^{11}Li : ⟷ ?







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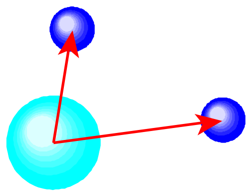
Three-body models

- few-nucleon dilute halo :
  - correlations overwhelm mean field...



$$\Psi \equiv \Psi(2n)$$
$$V(2n) = V_{cn}(1) + V_{cn}(2) + V_{nn}$$
$$H_{2n}\Psi(2n) = E_0\,\Psi(2n)$$

V_{nn}: zero range...

V_{cn}: "Woods-Saxon"...

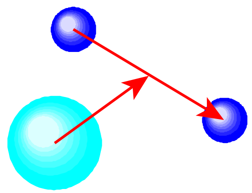
  - expand on core-n basis :

$$\Psi^{JM\pi} = \sum_{ij} c_{ij}\,|\phi^i_{cn} \otimes \phi^j_{cn}\rangle_{JM\pi}$$

  - Lagrange mesh :

$$\phi_{cn} = \sum_i^N f_i(r/h)\,Y_l(\Omega)\ \left[f_i(x_j) \propto \delta_{ij}\right]$$

- more complex formalisms :
  - Jacobi coordinates (x, y)



  - Hyperspherical Harmonics :

$$\Psi^{JM\pi} = \rho^{-5/2} \sum \chi^{LS}_{Kl_xl_y}(\rho)\,|\mathcal{Y}^{l_xl_y}_{KL}(\Omega_5) \otimes X_S\rangle_{JM\pi}$$

$\rho = \sqrt{x^2 + y^2}$ hyperradius

$K = l_x + l_y + 2n$ hypermoment

$$\left[-\frac{d^2}{d\rho^2} + \underbrace{\frac{(K+3/2)(K+5/2)}{\rho^2}}_{\text{effective HH barrier !}} - \frac{2m}{\hbar^2}E\right] f(\rho) = 0$$

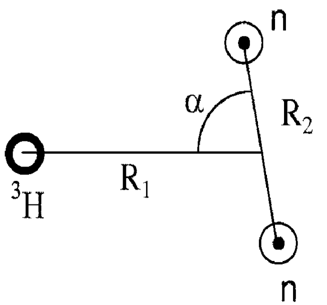
  - asymptotics from "$3 \longrightarrow 3$" scattering
  - still inert core and V_{cn}...

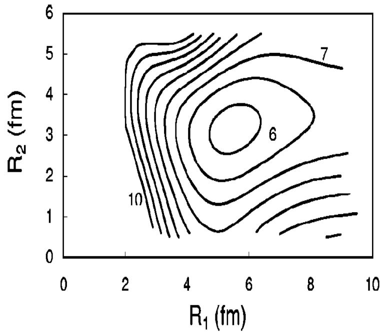
More-body models

▶ Generator Coordinate Method [^{5}H] :

$$H = \sum_i^5 T_i + \sum_{i<j} V_{ij}$$

$$\Phi_{\nu_1\nu_2\nu_3}(R_1, R_2, \alpha) = \mathcal{A}\{\phi_t^{\nu_1}\phi_n^{\nu_2}\phi_n^{\nu_3}\}$$





$$\Psi^{JM\pi} = \sum_{\substack{R_1R_2\alpha\\ \nu_1\nu_2\nu_3}} f^{J\pi}_{\nu_1\nu_2\nu_3}\, \Phi^{JM\pi}_{\nu_1\nu_2\nu_3}(R_1, R_2, \alpha)$$

▷ core excited states !

▷ a priori clustering

▷ HO [same b] wave functions…

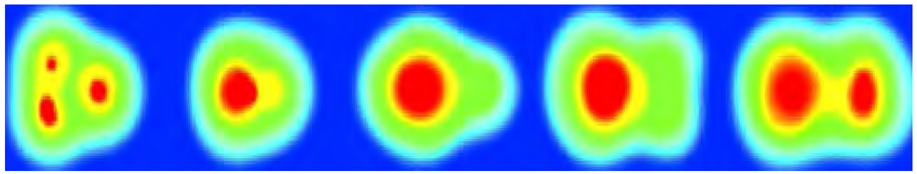
▷ very effective V_{NN}…

▶ Antisymmetrized Molecular Dynamics :

$$H = \sum_i^A T_i + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk}$$

$$\Phi_{\mathsf{AMD}}(X_i, \nu) = \mathcal{A}\{\phi_1, \phi_2, \cdots, \phi_A\}$$

$$\Psi^{JM\pi} = \sum_j c_j\, \Phi^{JM\pi}_{\mathsf{AMD}}(X_i^j)$$



[$^{11-19}$B]

▷ A wave packets ! [Gaussian]

▷ NO assumptions… (???)

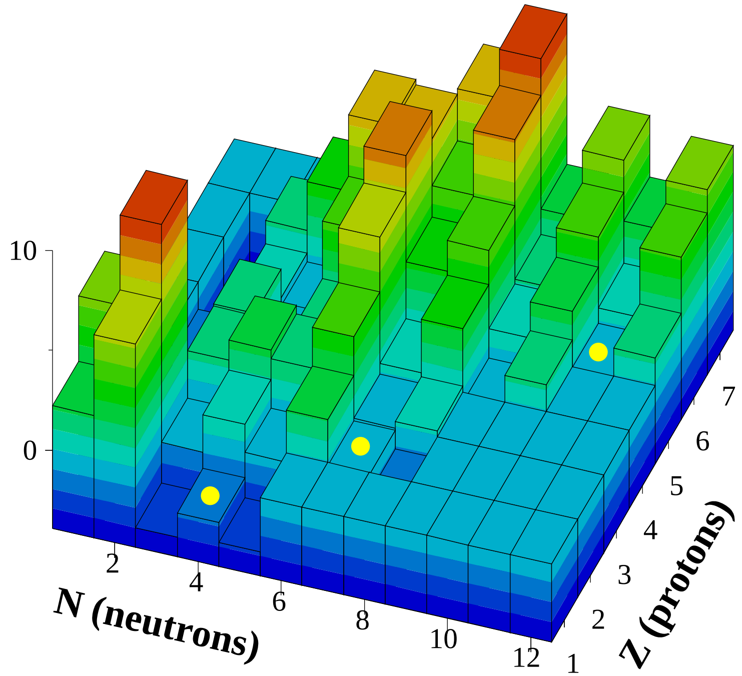
▷ V_{NN} as effective as in GCM

▷ $V_{ijk} \propto \delta(r_i - r_j)\,\delta(r_i - r_k)$ …

▷ "valence" neutrons :

$$\{\phi_i\} \rightarrow \{\phi'_\alpha\}_{\mathsf{o.n.}} \rightarrow h_{\alpha\beta} \rightarrow E_\alpha$$

Formation of unbound nuclei



- how to dive into the sea ?
  - ▷ strip nucleons from a beam !
- how to find a "nucleus" ?
  - ▷ look for energy levels ...

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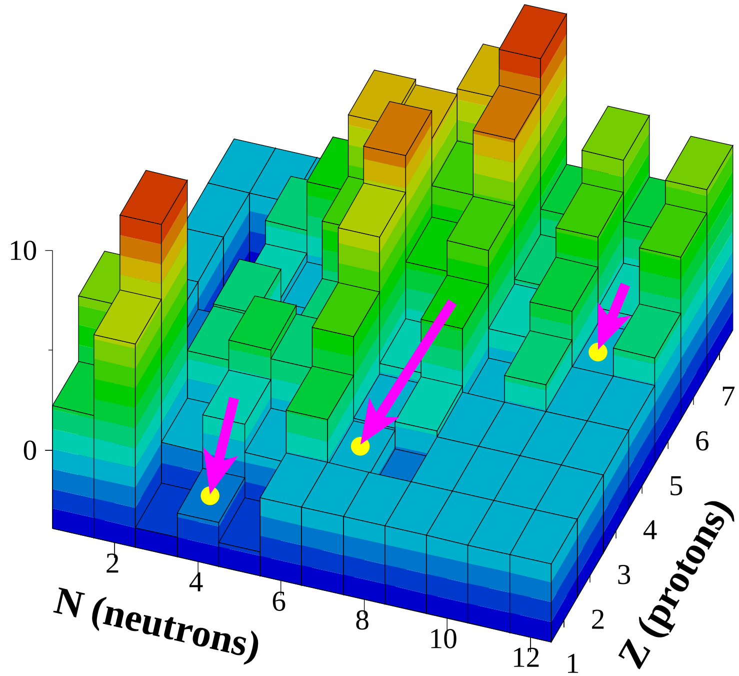

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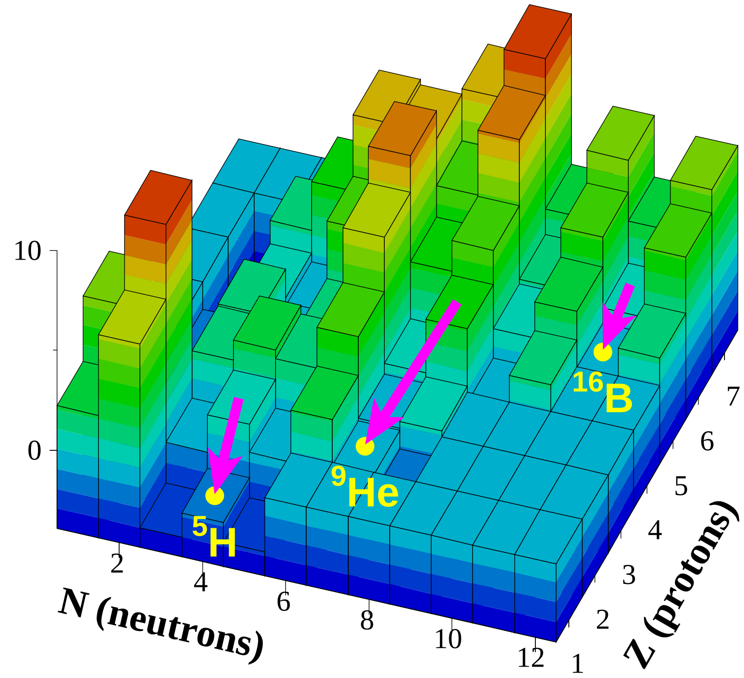

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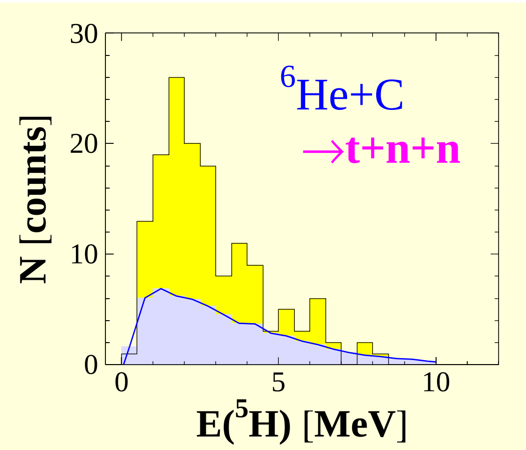
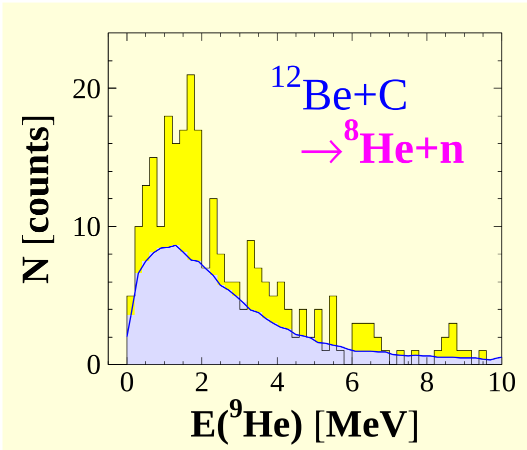
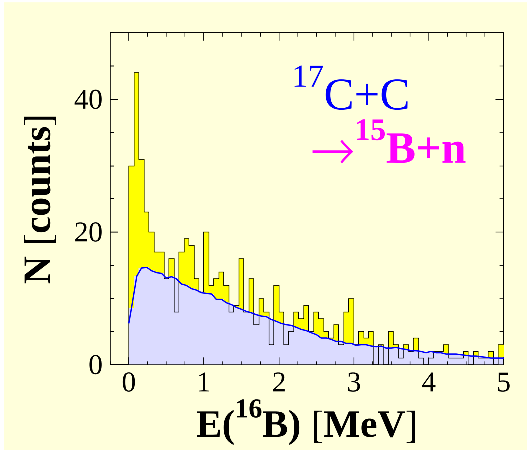




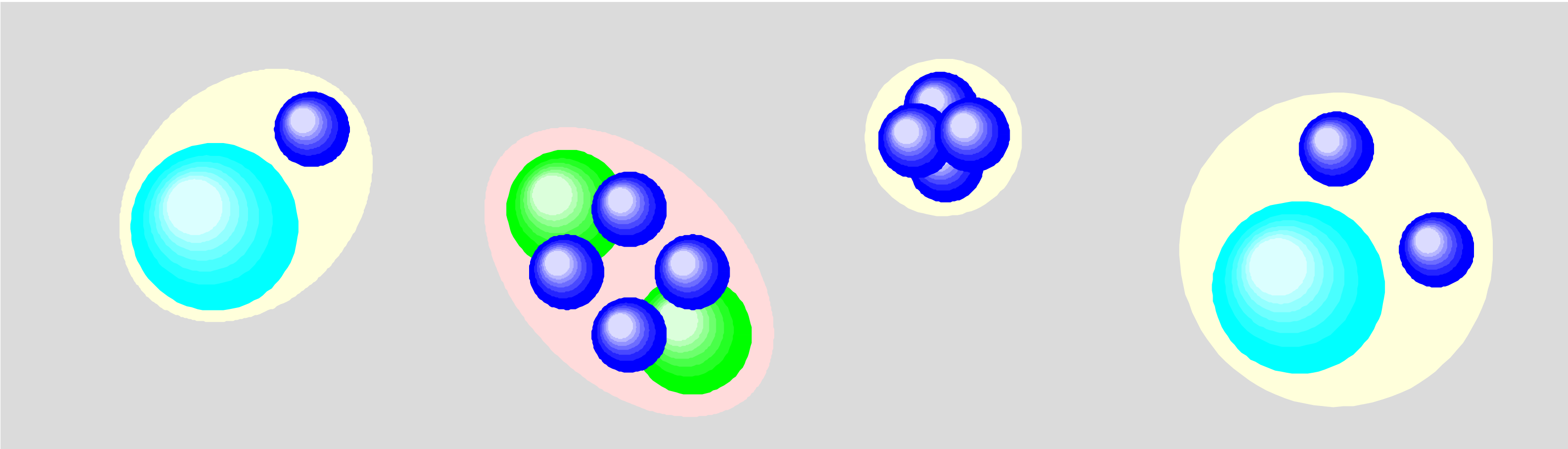


Exotic exotic nuclei (II)

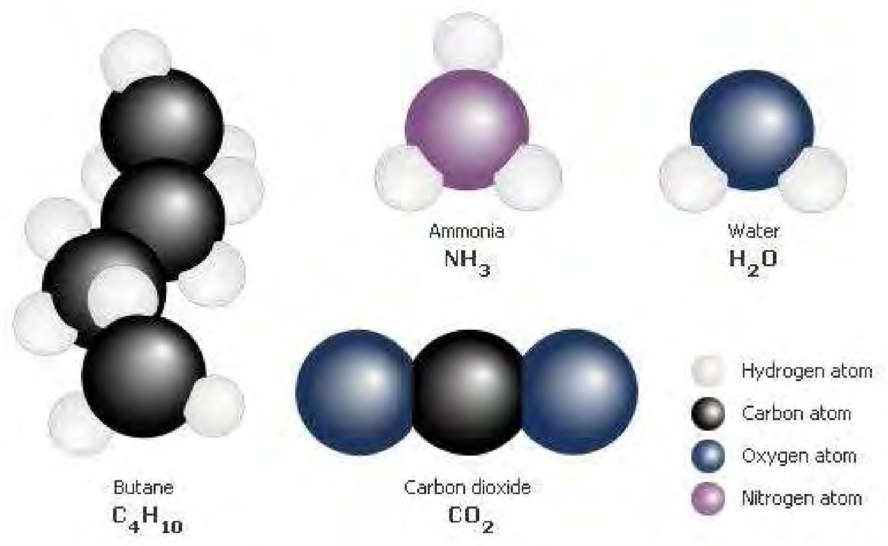
(I) The Nuclear Halo

(II) Nuclear Molecules

(III) Neutron Clusters ?



Molecules and nuclei



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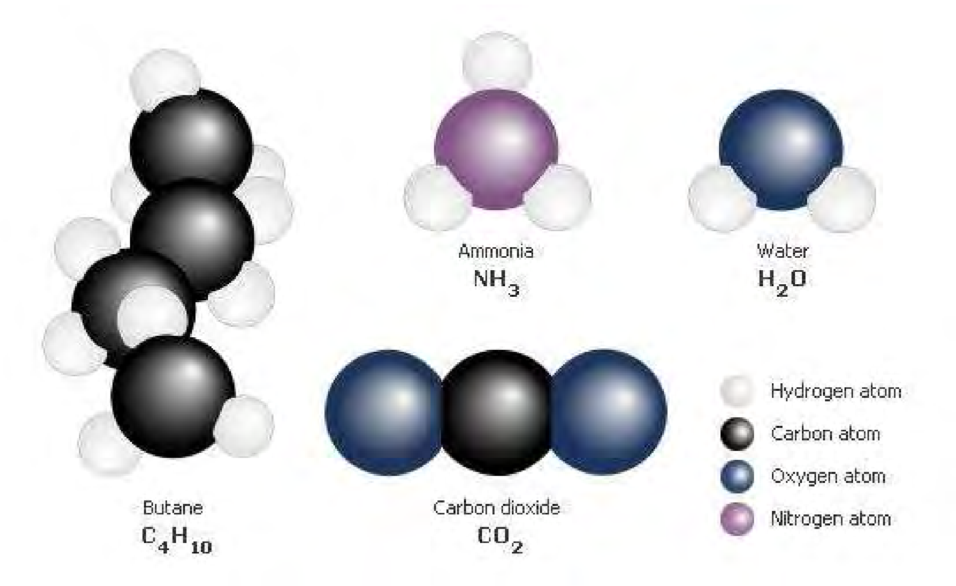
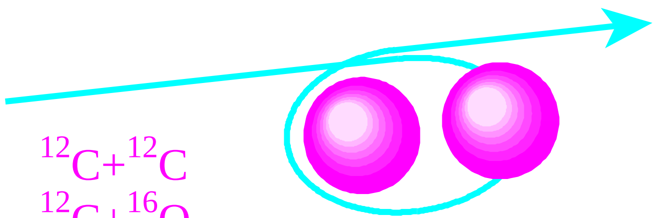


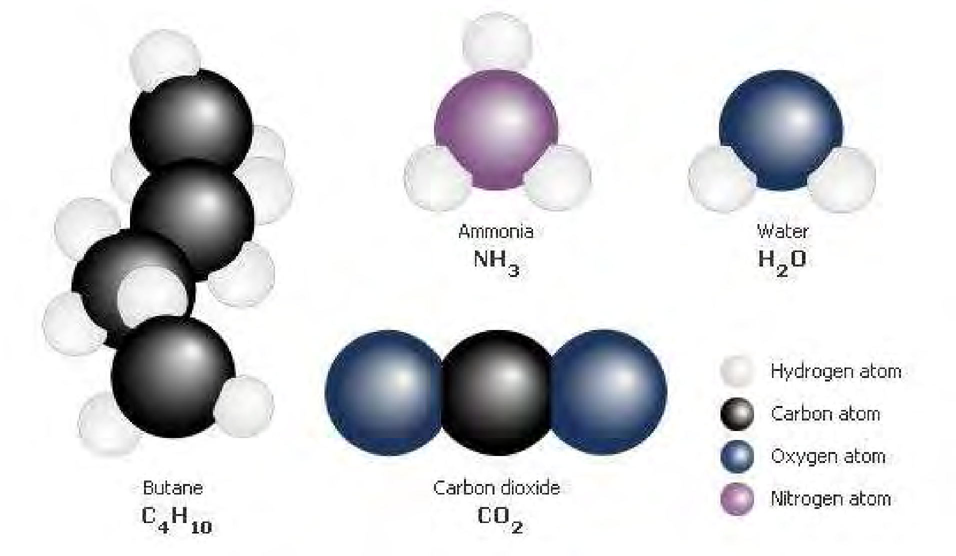
- scattering resonances :



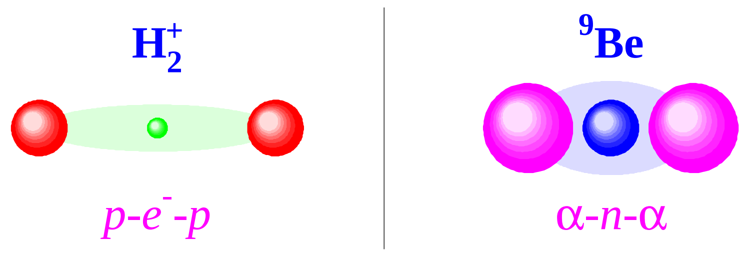
$^{12}C+^{12}C$
$^{12}C+^{16}O$
$^{16}O+^{16}O$

  - ▷ E^* vs $J(J+1)$ systematics
  - ▷ very sharp : $\sim$100 keV
  - ▷ orbiting : molecule-like properties !

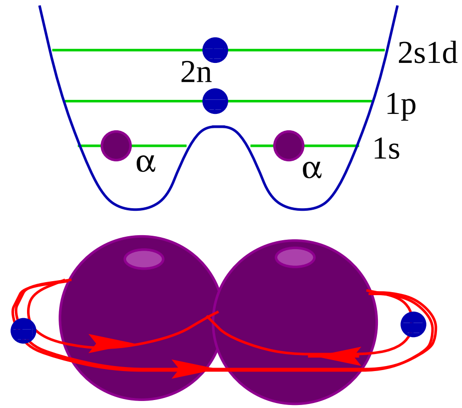
Molecules and nuclei



- covalent molecules ?

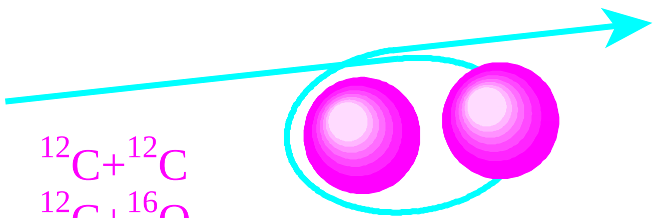


- two-center potential [^{10}Be] :



- ▷ two-center orbits !
- ▷ binding from nucleon exchange !!

- scattering resonances :



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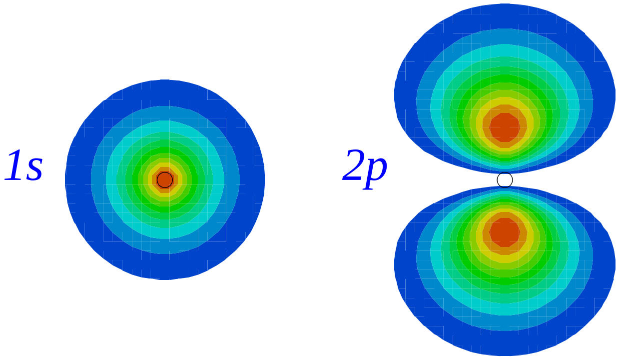
Atomic orbitals

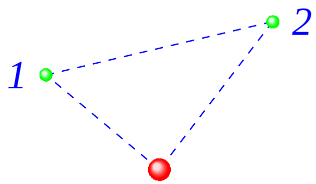
- the hydrogen (and -like) atom :

$$H = -\frac{1}{2}\nabla^2 - \frac{Z}{r}$$
$$E_n = -\frac{Z^2}{2n^2}$$

  - atomic orbitals : $|\phi|^2$



- the helium atom :



$$H = -\frac{1}{2}[\nabla_1^2 + \nabla_2^2] - \frac{2}{r_1} - \frac{2}{r_2} + \frac{1}{r_{12}}$$

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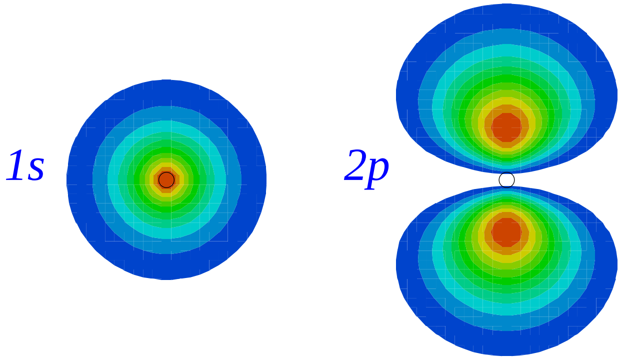

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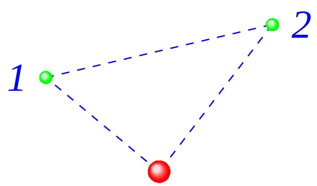


$$H = -\tfrac{1}{2}[\nabla_1^2 + \nabla_2^2] - \tfrac{2}{r_1} - \tfrac{2}{r_2} + \tfrac{1}{r_{12}}$$

- neglect electron "correlation" :

$$H' = -\tfrac{1}{2}[\nabla_1^2 + \nabla_2^2] - \tfrac{Z'}{r_1} - \tfrac{Z'}{r_2}$$
$$\Psi = \phi_H(1)\,\phi_H(2)$$

$\rightsquigarrow E = E_H(1) + E_H(2)$ +38%

$\rightsquigarrow \langle\Psi|H|\Psi\rangle$ +5%

$\rightsquigarrow \Phi(Z')$: $Z' = 2 - \tfrac{5}{16}$ +2%

▷ electrons screen each other ...

- more complex atoms :

$$H = -\tfrac{1}{2}\textstyle\sum_i \nabla_i^2 - \sum_i^N \tfrac{Z}{r_i} + \sum_{i<j} \tfrac{1}{r_{ij}}$$
$$\Psi = \Pi_i^N \phi_H(i)$$

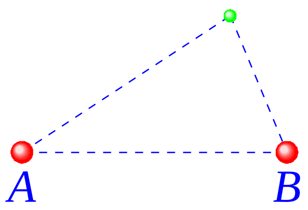
$\approx N$ one-electron $[Z']$ problems !

"True" molecules

Why do they form at all (and how) ?

Melvin W. Hanna (1965)

▶ the simplest molecule : $\mathbf{H_2^+}$



$$H = -\frac{1}{2}\sum_i \nabla_i^2 - \frac{1}{r_A} - \frac{1}{r_B} + \frac{1}{R_{AB}}$$

▷ Born-Oppenheimer : fix nuclei…

▷ variational principle : LCAO

$$\Psi_\pm = (\phi_A \pm \phi_B)$$

$$E_\pm = \langle \phi_A | H_A | \phi_A \rangle + \langle \phi_B | H_B | \phi_B \rangle + \left\{ \frac{1}{R_{AB}} - 2\langle \phi_A | \frac{1}{r_B} | \phi_A \rangle \right\} \mp \langle \phi_A | H | \phi_B \rangle$$

+Coulomb –exchange terms !

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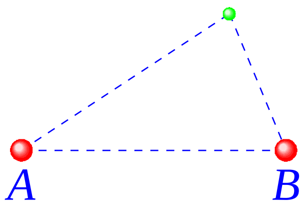

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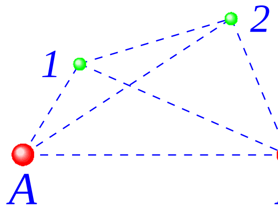
+Coulomb −exchange terms !

▶ next : the H_2 molecule



$$H = H_1^+ + H_2^+ - \frac{1}{R_{AB}} - \frac{1}{r_{12}}$$

$$\Psi = \phi^+(1)\,\phi^+(2)$$

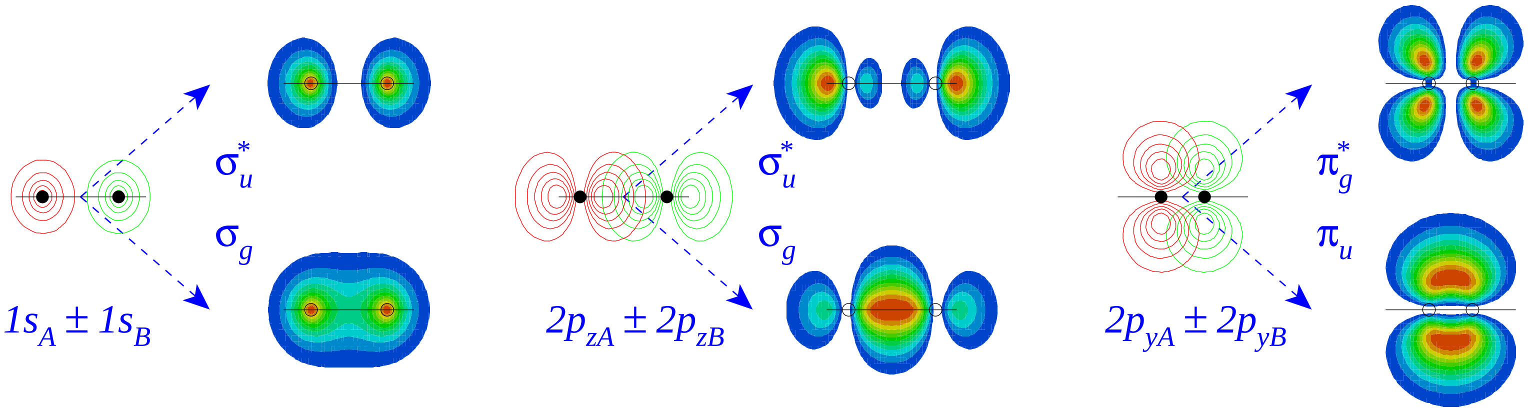
▷ different Ψ_{MO} approximations :

⇝ $\phi_{\{AB+BA\}} + \phi_{\{A^+B^-+A^-B^+\}}$	+6.4%
⇝ $\phi_{\{AB+BA\}}$	+4.9%
⇝ $\phi_{\{AB+BA\}} + \lambda\,\phi_{\{A^+B^-+A^-B^+\}}$	+4.7%
⇝ $\{1s + \lambda\,2p\}_{\{AB+BA\}}$	+4.2%

The best function has 50 variational terms. Unfortunately, all intuitive concepts dissapear. It is still an open question whether accurate calculations will solve fundamental problems…

The chemical bond

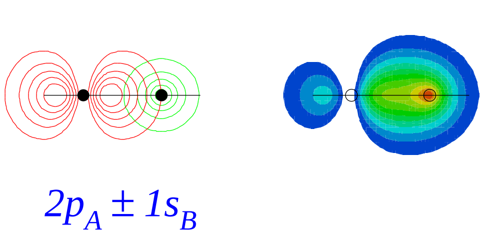
▶ MO theory and LCAO :



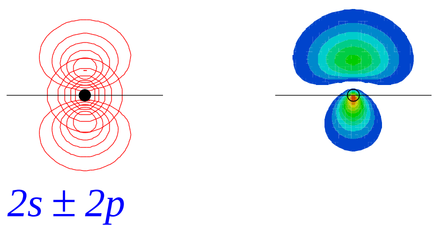
▷ $\Psi_{\pm m}$: σ, π, δ ...

▷ $(2N)_{AO} = (N + N^*)_{MO} \longrightarrow$ stability !

▶ proportions [H_2O] :



▶ geometries [$sp^3 \longrightarrow 109°$...] :

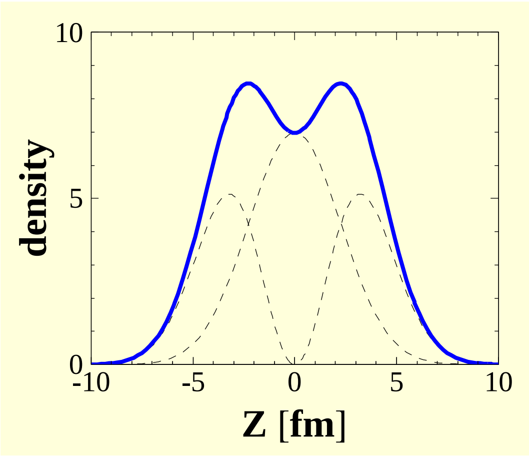


Molecular orbitals

▶ deformed harmonic oscillator :

$$V = m\,\omega_0{}^2\,r^2/2 \;\longrightarrow\; (\omega_t, \omega_z)$$
$$E = \hbar\,\omega_0\,(N+3/2) \;\longrightarrow\; (n_t, n_z)$$

▶ ^{8}Be $[\alpha+\alpha]$: $\omega_t/\omega_z = 2$



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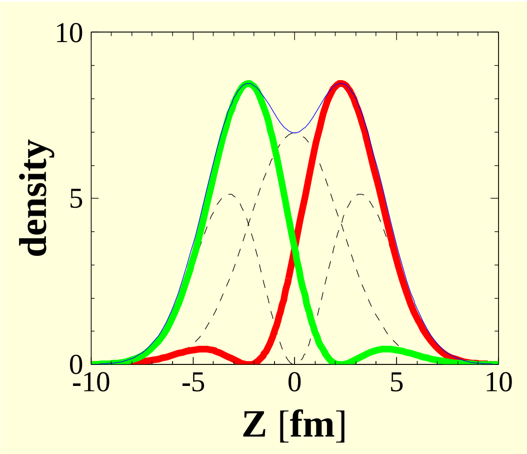

$$\psi_1 = (\psi_{00}+\psi_{01})/\sqrt{2}$$
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$$\langle\psi_{1,2}|\psi_\alpha\rangle \approx 0.9 \;!$$

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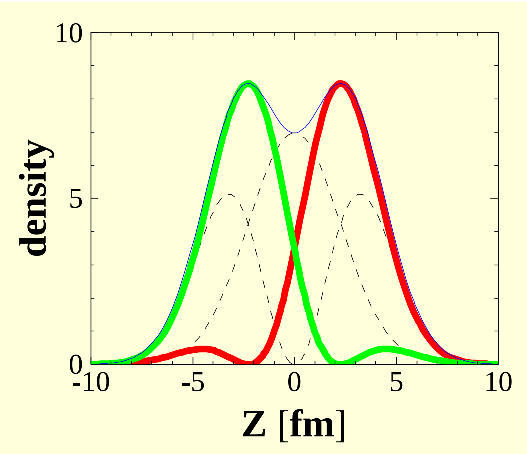

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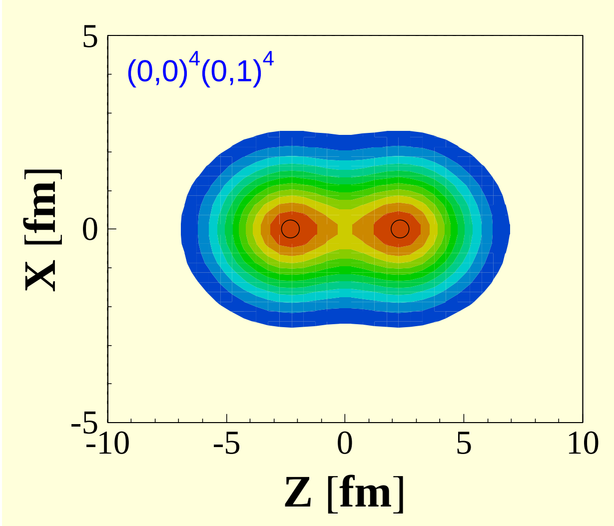

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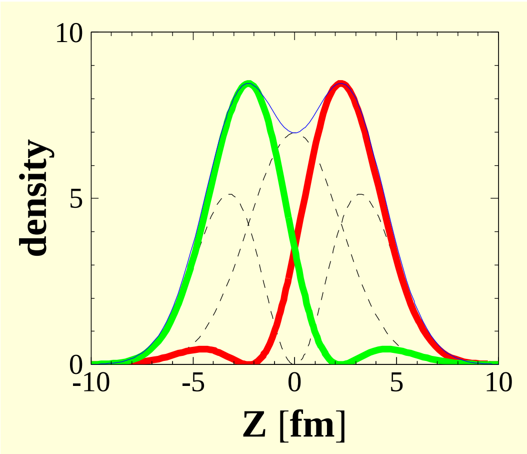

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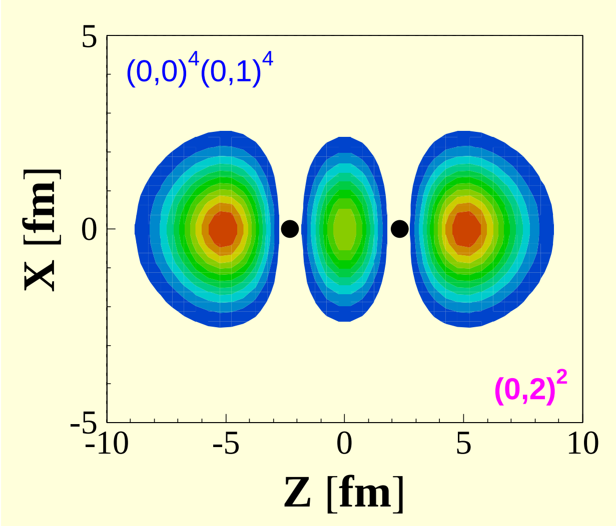

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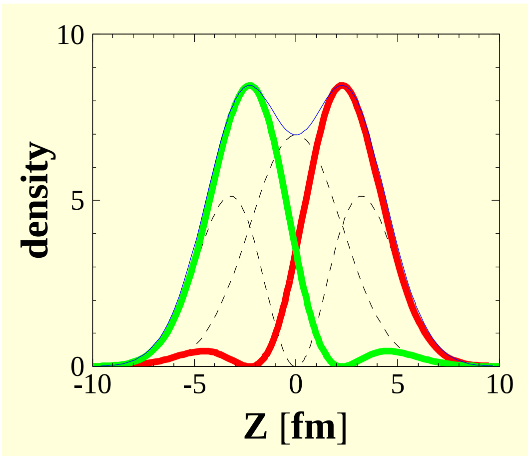

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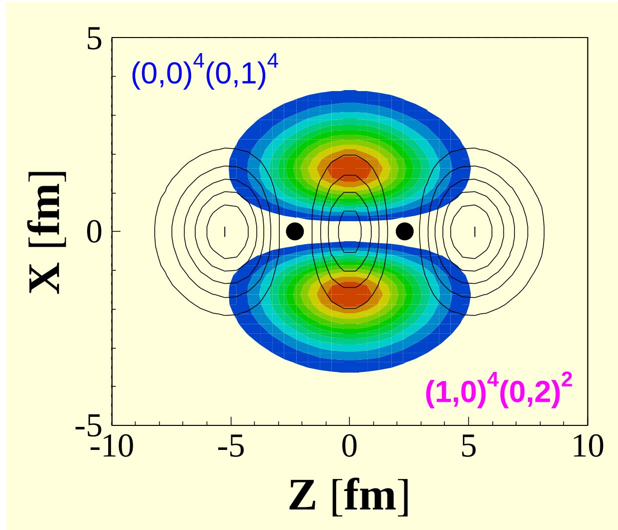

▷ LCNO : σ, π MO ! [^{15}Be : σ^*, π^*...]

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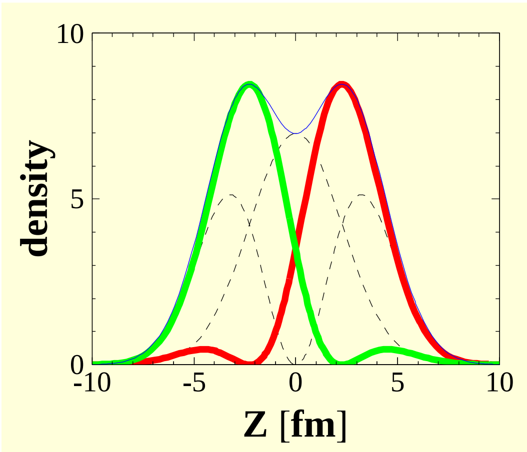

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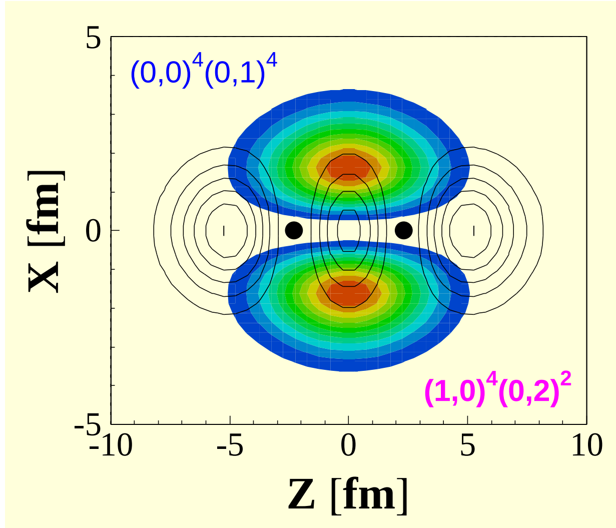

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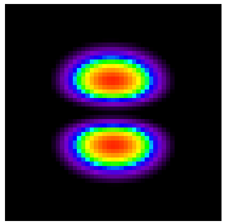
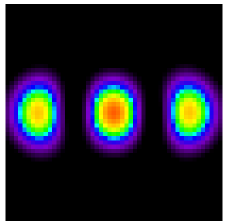
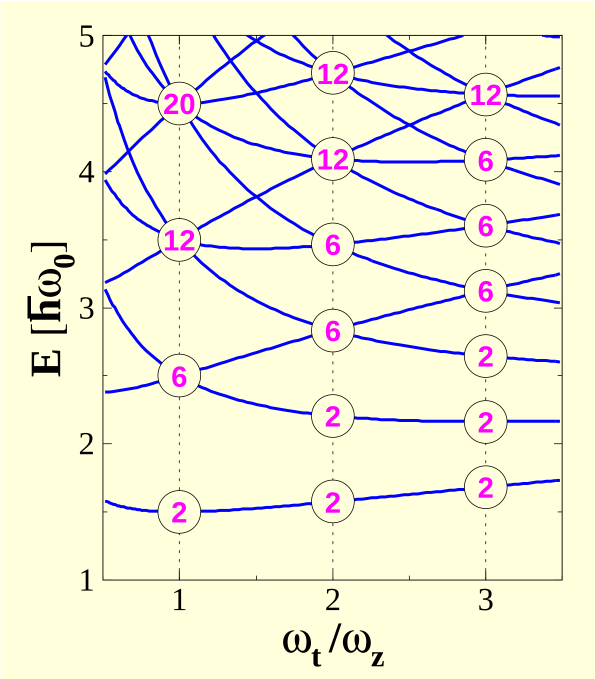
- AMD calculations [^{10}Be] :

$0^+_1\,[\pi^2]$   $0^+_2\,[\sigma^2]$

Deformation and clustering

▶ deformed HO level scheme :



$$E = \hbar\,\omega_0\left([n_x+n_y+n_z]+3/2\right)$$
$$\rightarrow \hbar\,\omega_t\,(n_t+1) + \hbar\,\omega_z\,(n_z+1/2)$$

▷ new magic numbers !

▷ ^{8}Be, ^{20}Ne, ^{24}Mg, ^{12}C$^{*/\mathrm{gs}}$ ...

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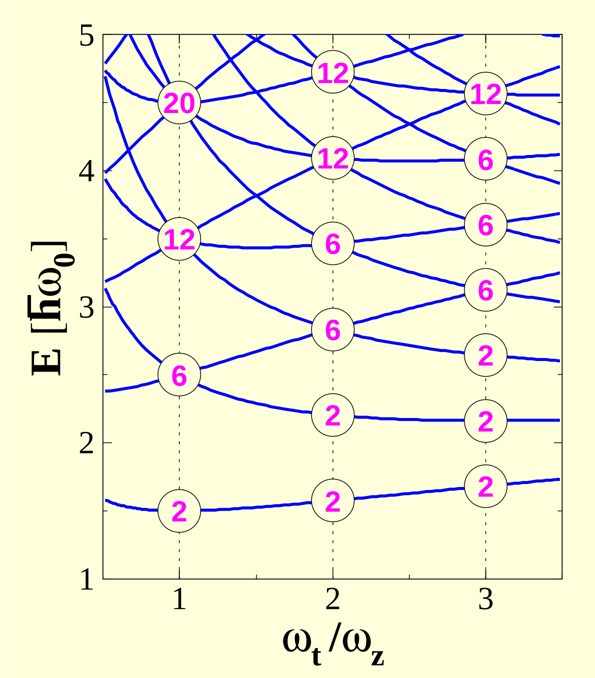

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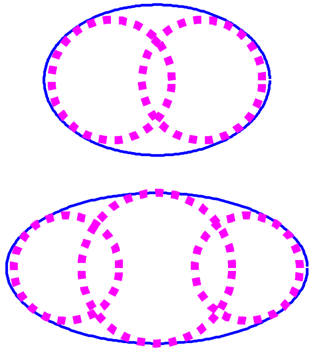
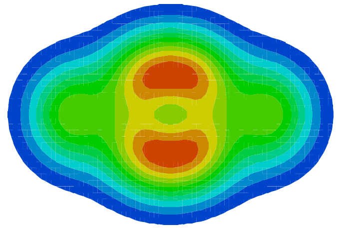
▷ spherical degeneracies repeated !





^{24}Mg ≡ α ^{16}O α

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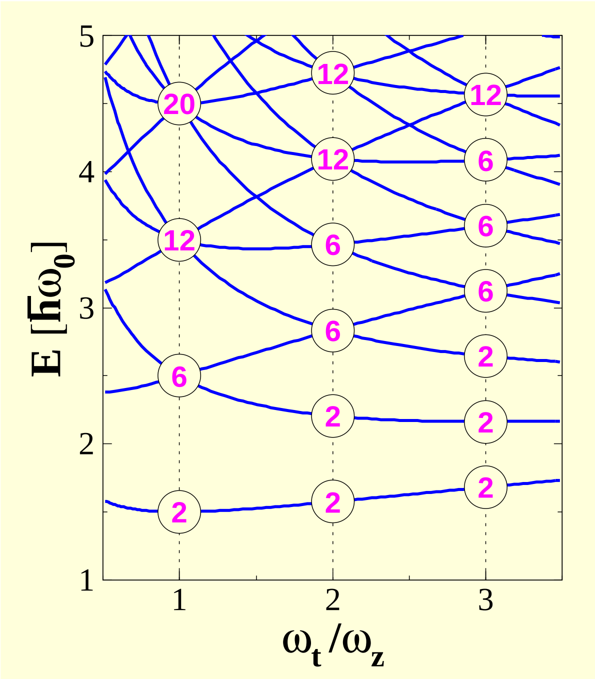

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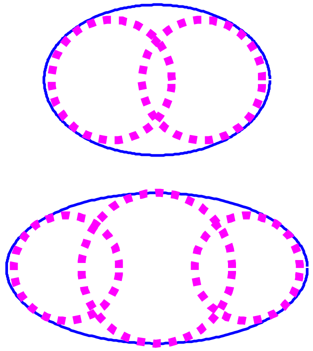
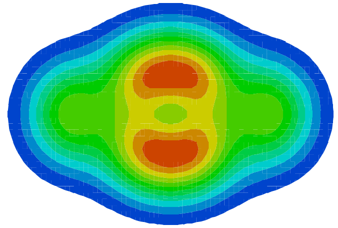


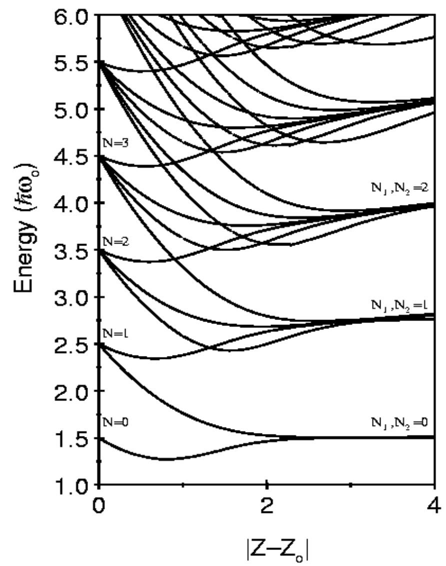


^{24}Mg ≡ α ^{16}O α

▶ two-center HO :

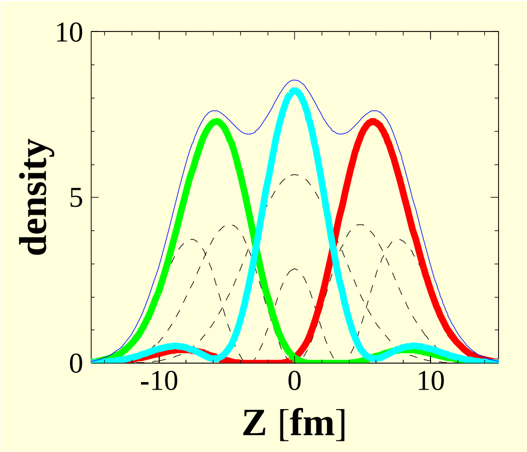
▷ fission

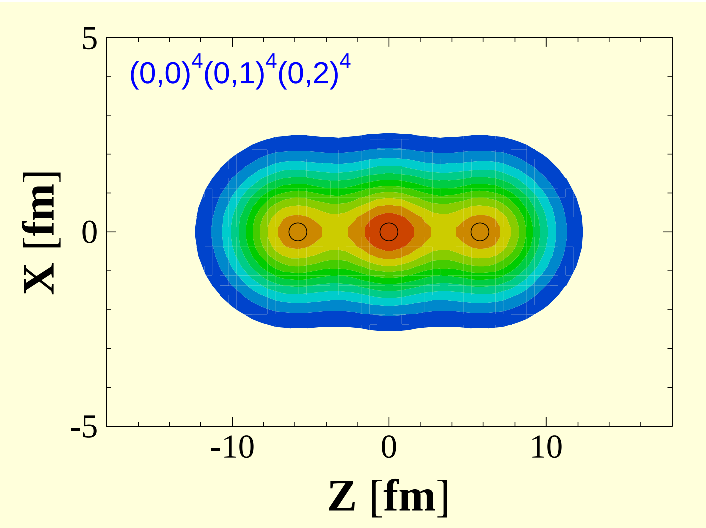
▷ fusion



Binding more complex molecules

▶ three centers $[\omega_t/\omega_z = 3]$: ^{12}C





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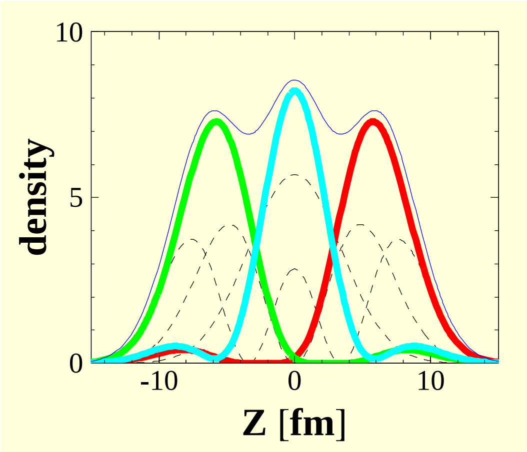

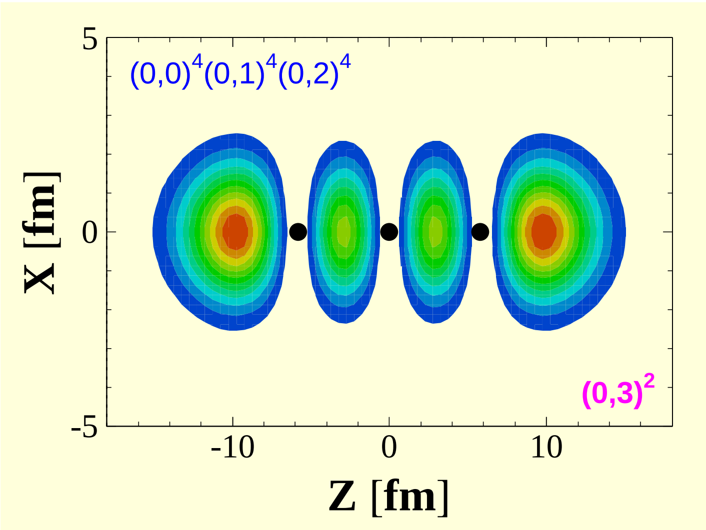

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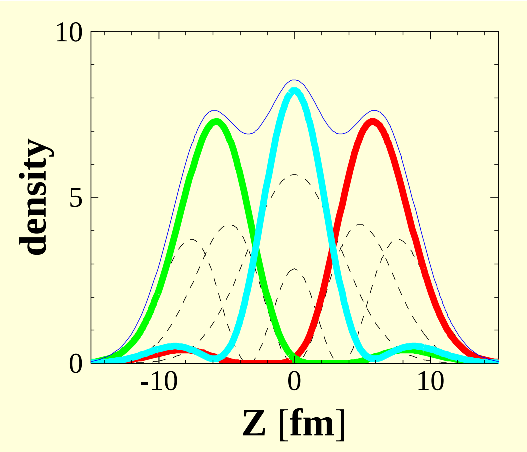

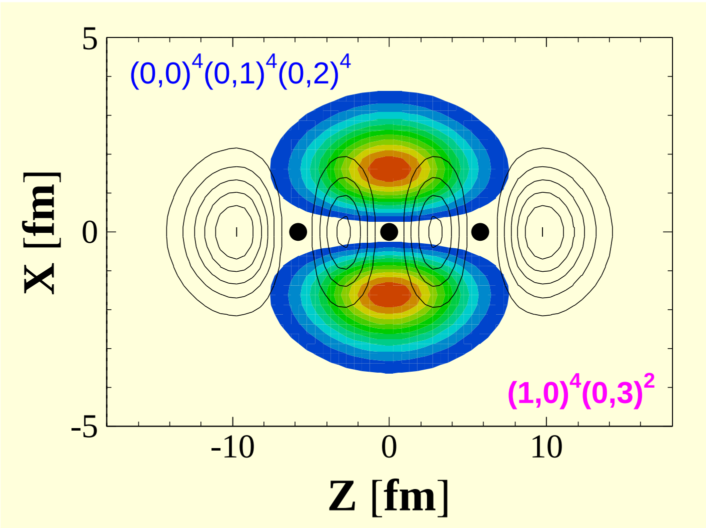

Binding more complex molecules

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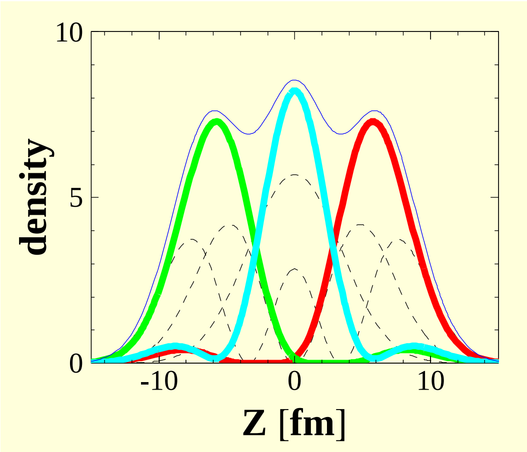

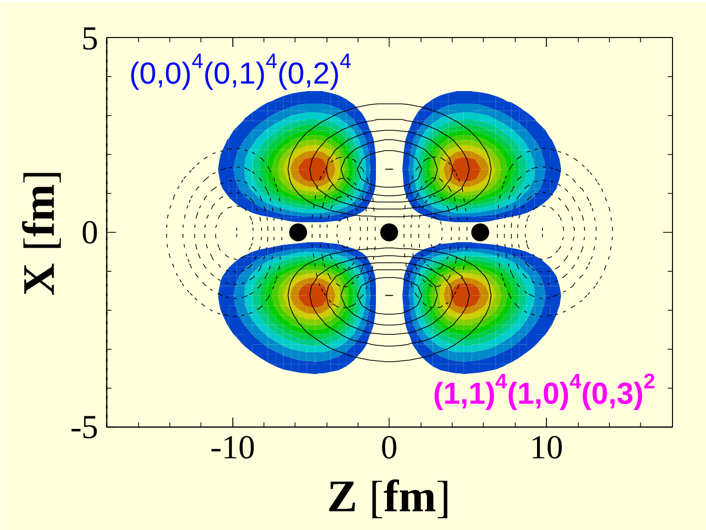

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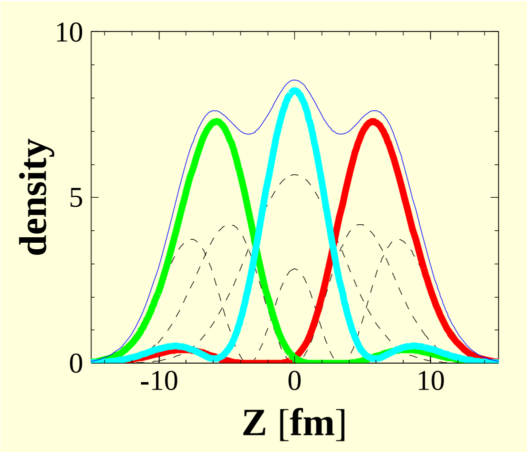
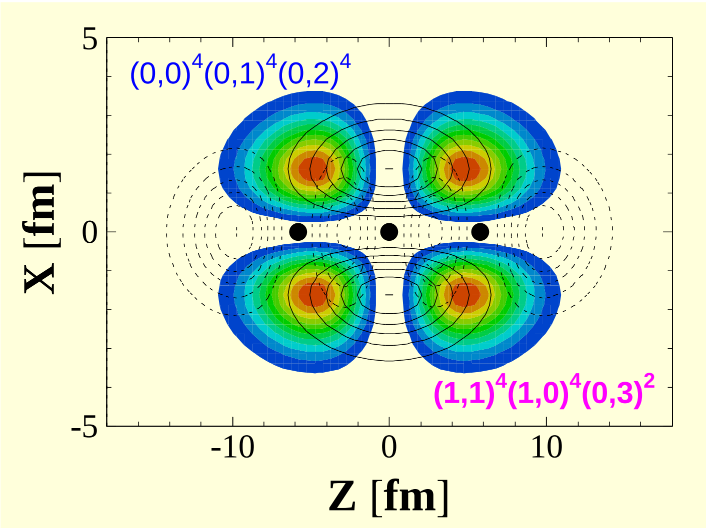
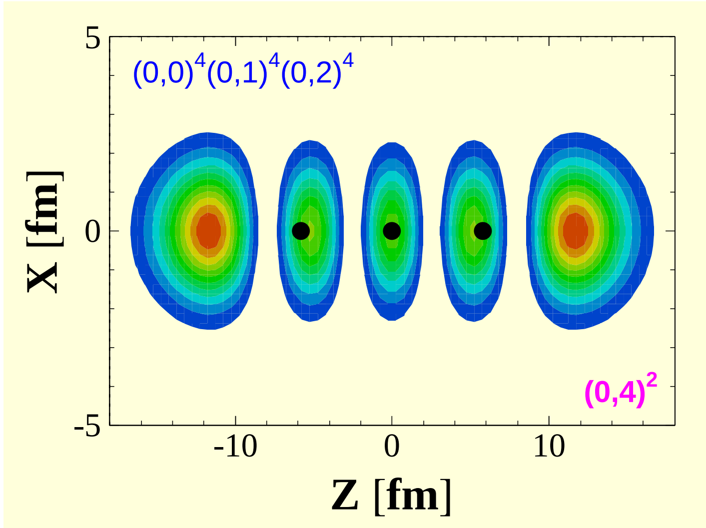




▶ beyond ^{22}C : σ^*, π^*...



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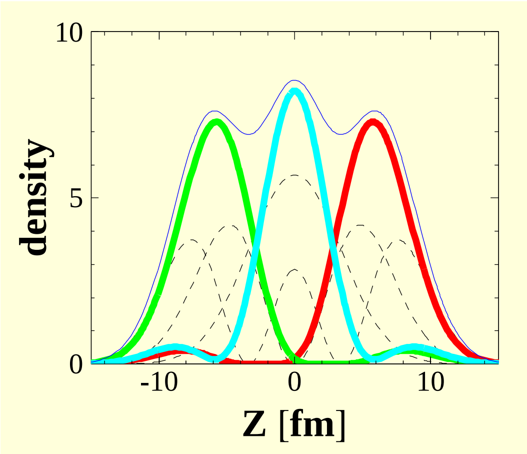

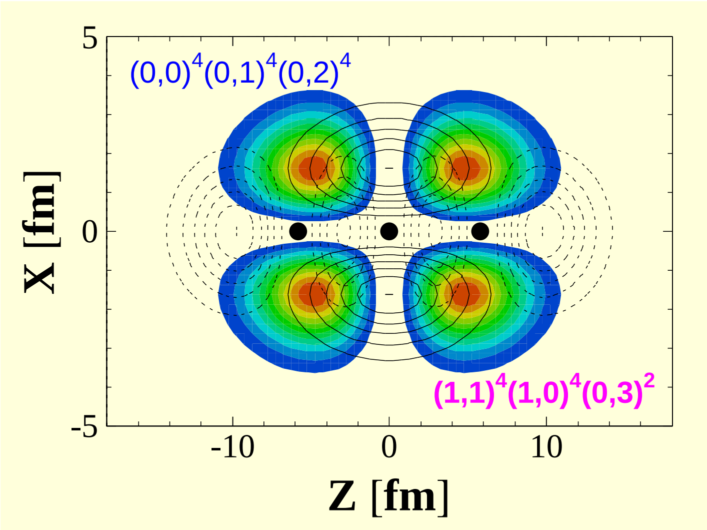

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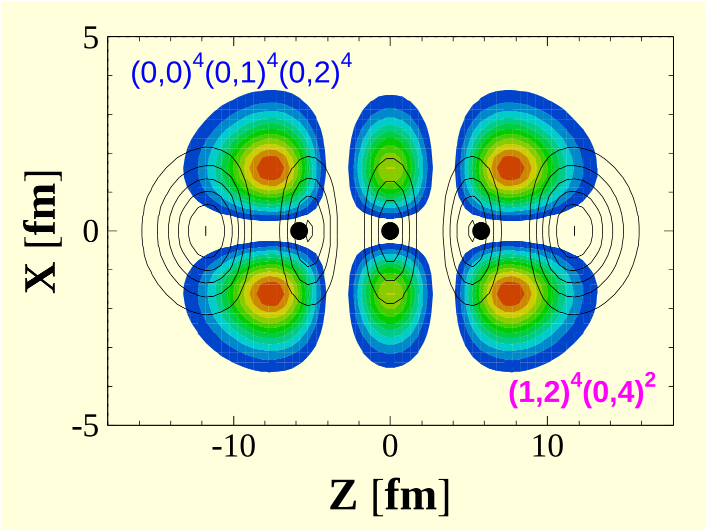

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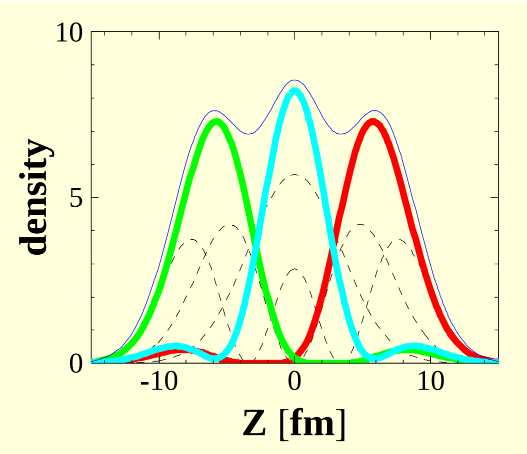

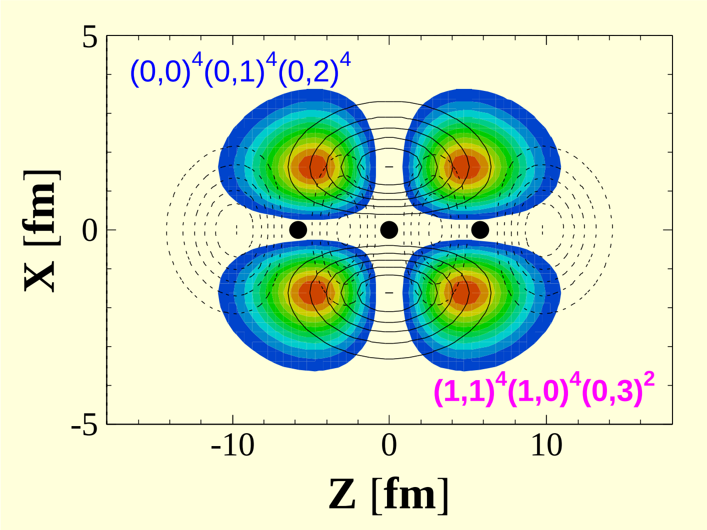

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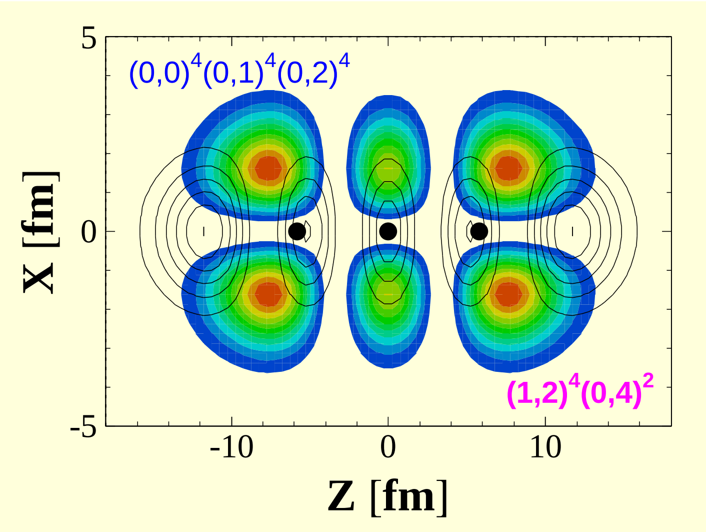
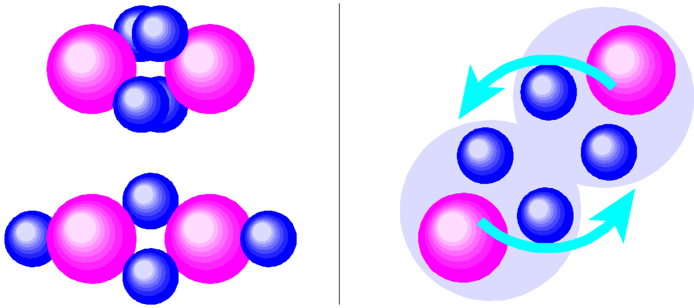
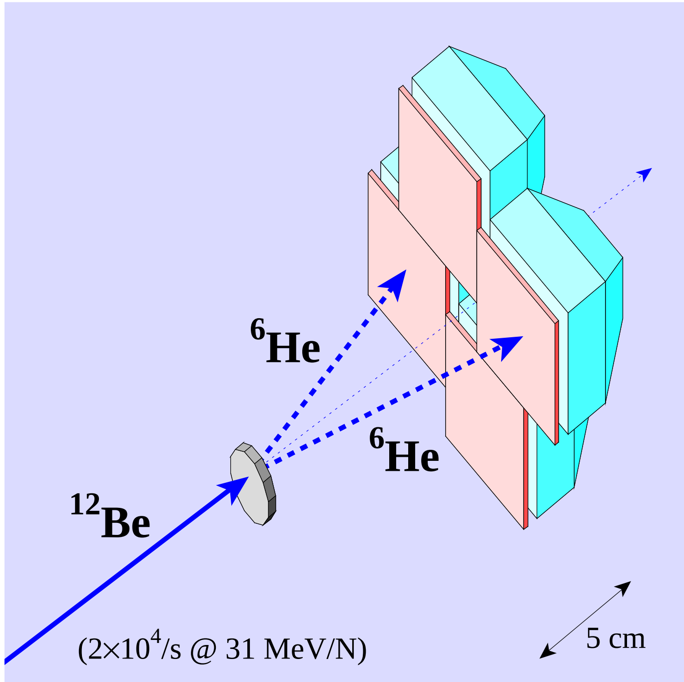


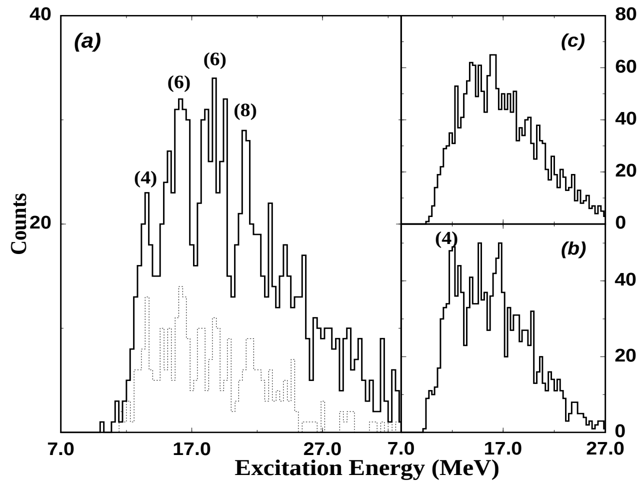
▸ heavier molecules ? [^{12}Be]



A halo around another halo

▶ inelastic excitation of ^{12}Be :





▷ just breakup or ^{12}Be$^{*} \longrightarrow {}^{6}$He + ^{6}He ?

▷ are they associated to α-4n-α ?

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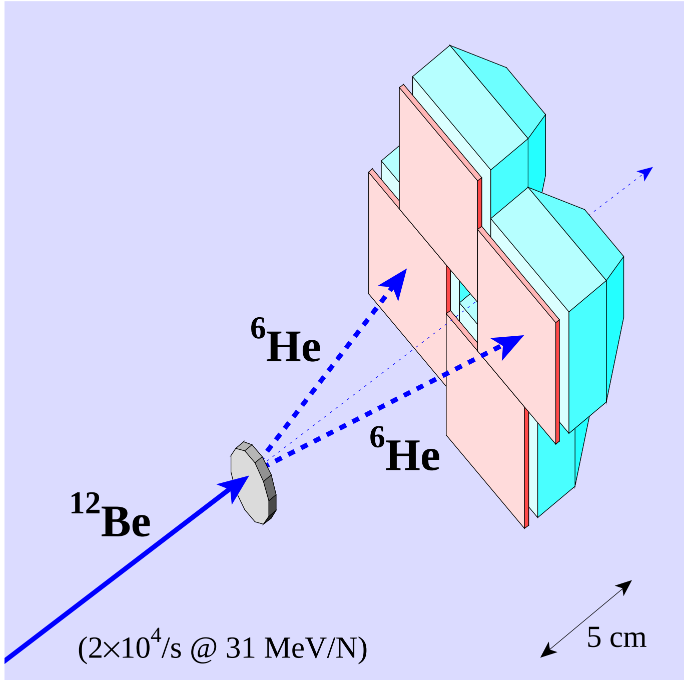

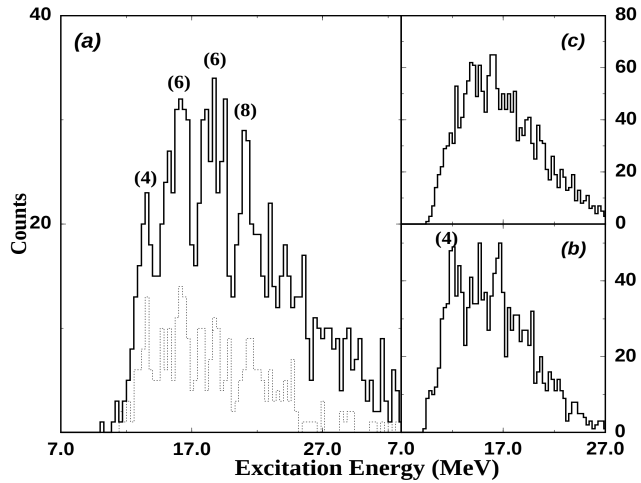

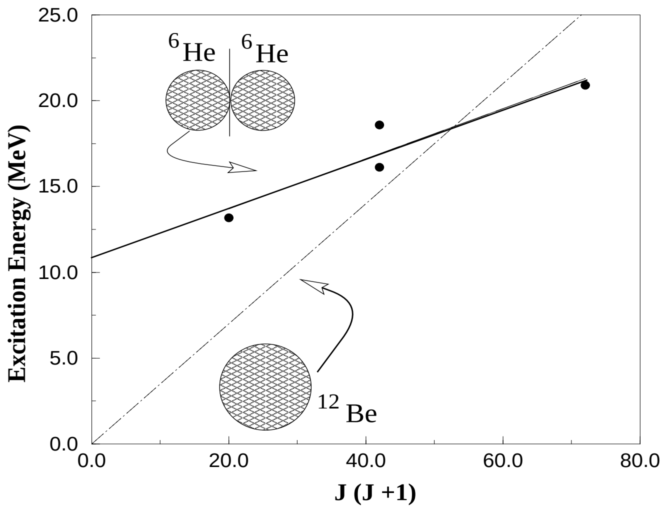

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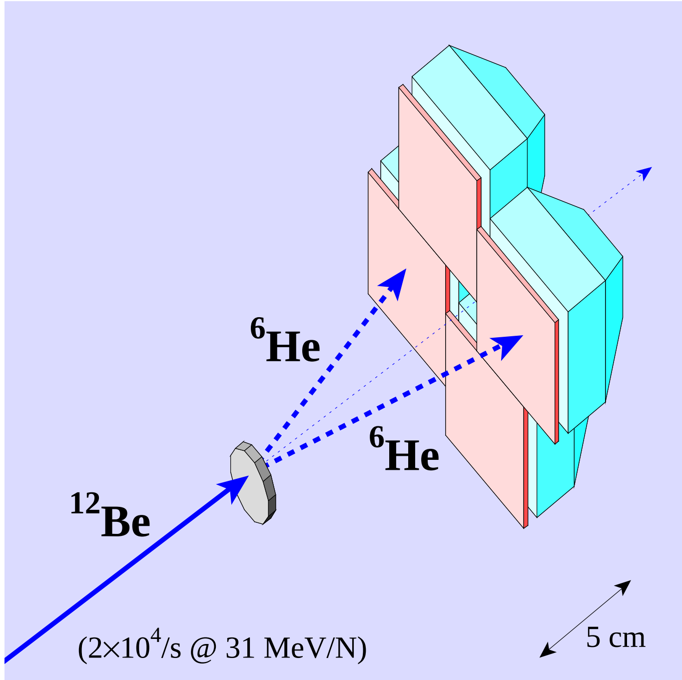
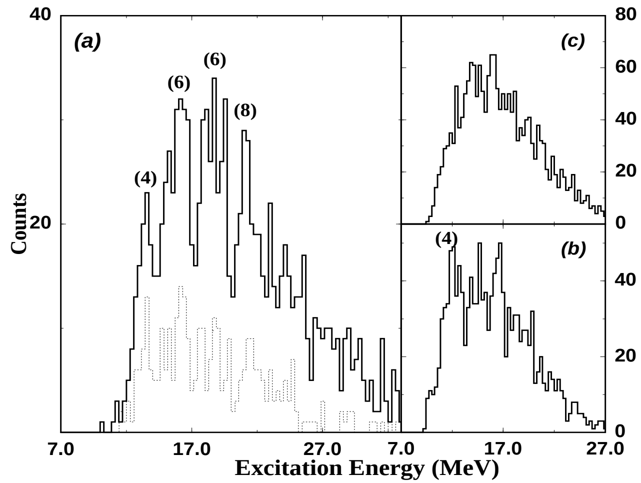
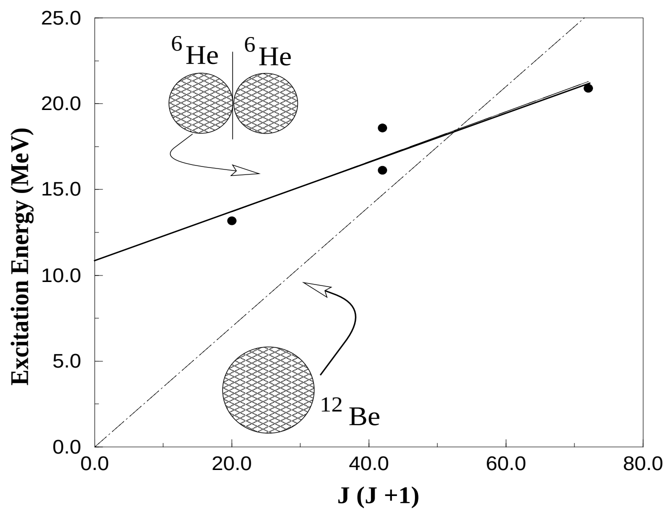






▷ just breakup or $^{12}\mathrm{Be}^{*} \longrightarrow {}^{6}\mathrm{He} + {}^{6}\mathrm{He}$?

▷ are they associated to α-$4n$-α ?

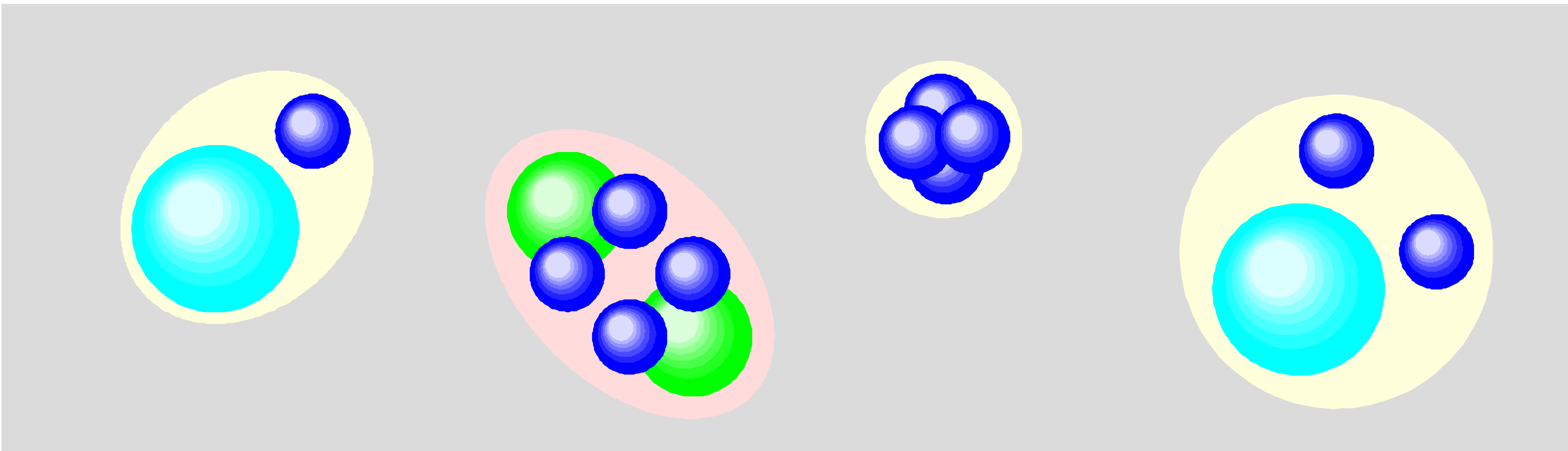
▶ missing mass $\left[{}^{9}\mathrm{Be}({}^{13}\mathrm{C},{}^{11}\mathrm{C}){}^{11}\mathrm{Be}^{*}\right]$ …

Exotic exotic nuclei (III)

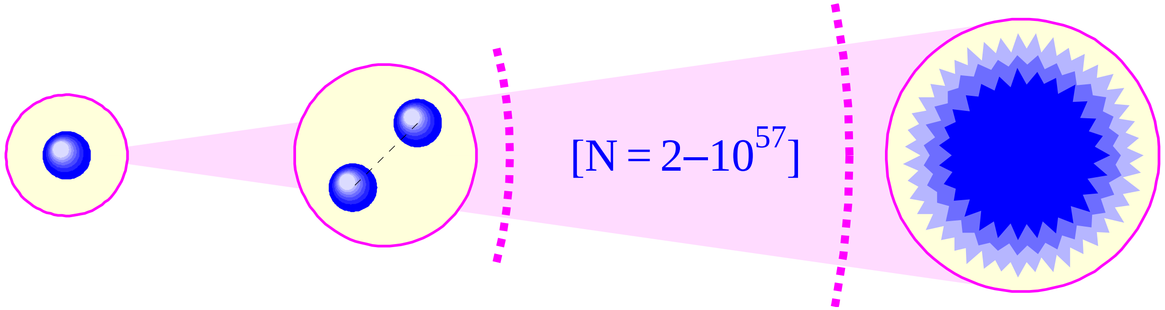
(I) The Nuclear Halo

(II) Nuclear Molecules

(III) Neutron Clusters ?



More than 2 neutrons



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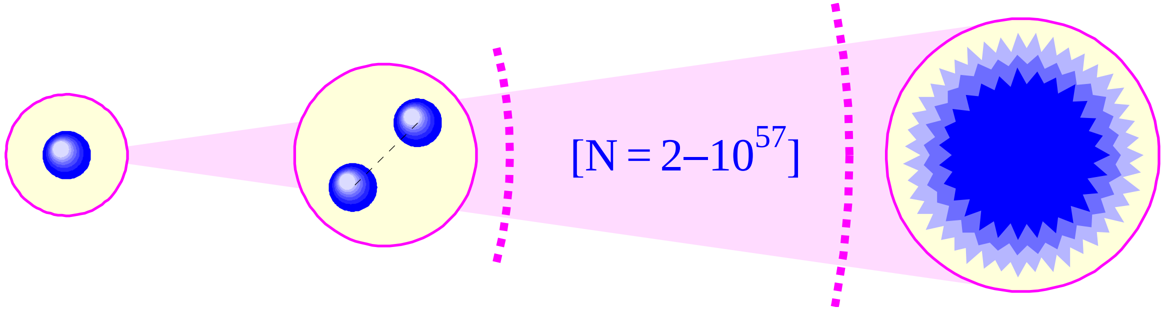
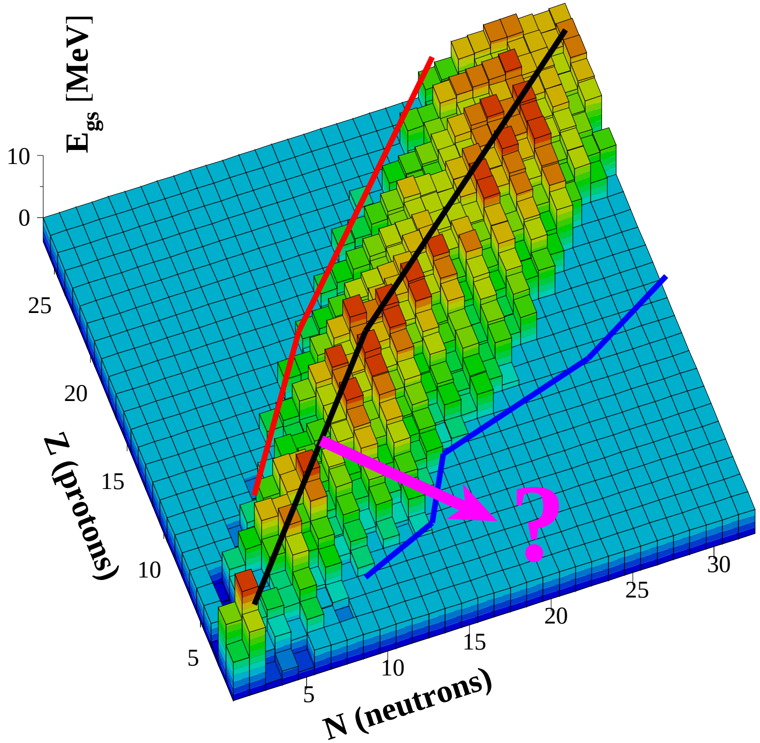




- neutron-rich beams :
  - ⇝ $\boldsymbol{N \gtrsim 2}$???

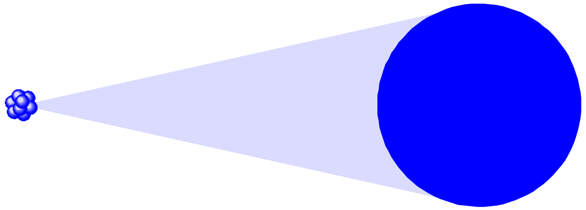
Neutron stars : from few to 10^{57}

▶ a huge liquid, neutral drop :

$$B/A \approx (a_v - a_a) + \frac{3}{5} G \frac{m_n^2}{r_0} A^{2/3}$$

▷ $(A_{min})_{B>0}$ depends on a_a !!!

a_a [MeV]	A_{min}	R [km]	$M/M_\odot$
23	$4\cdot 10^{55}$	3.4	0.04
$28 - \frac{33}{A^{1/3}}$	10^{57}	10	1



▷ roughly a neutron star…

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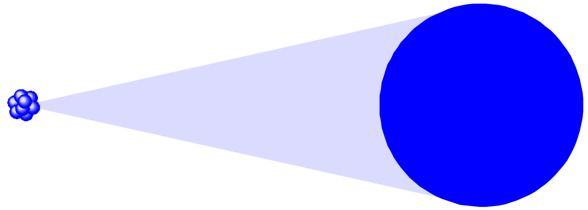


▷ roughly a neutron star…

- Fermi gas model :

$$^{56}\mathrm{Fe} + 26\,e^- \longrightarrow 56\,n + 26\,\nu_e$$

▷ Fermi pressure vs gravity :

$$\langle E_{kin}/N \rangle \propto (N/R^3)^{2/3}$$

$$\langle E_{pot}/N \rangle = -\frac{3}{5} G \frac{N m_n^2}{R}$$

$$\frac{\mathrm{d}}{\mathrm{d}R} \langle E/N \rangle = 0$$

▷ for $M = 1.5\,M_\odot$:

⇝ $R = 12$ km

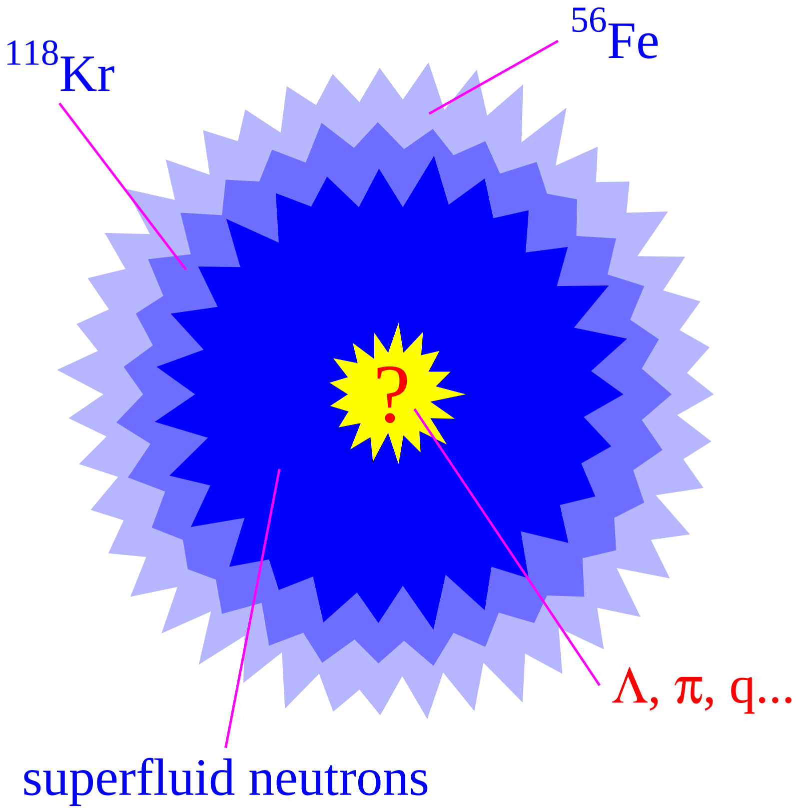
⇝ $\rho = 1.5\,\rho_{nuc}$

- ρ can be higher : Λ, quarks …

Neutron stars : from 10^{57} to few ?

▶ the ^{56}Fe$\rightarrow 56n$ collapse :

ρ [g/cm^3]	stage
10^9	p capture e^-
10^9–10^{11}	n-rich nuclei
10^{11}	n drip
10^{12}	superfluid n pairs
$2{\cdot}10^{14}$	nuclei dissolve
$> 4{\cdot}10^{14}$	superfluid n + ?



▷ rotation period ∼ ms !!!

▷ magnetic field ∼ 10^{14} G !!!

▷ ^{A}n in inner crust ?

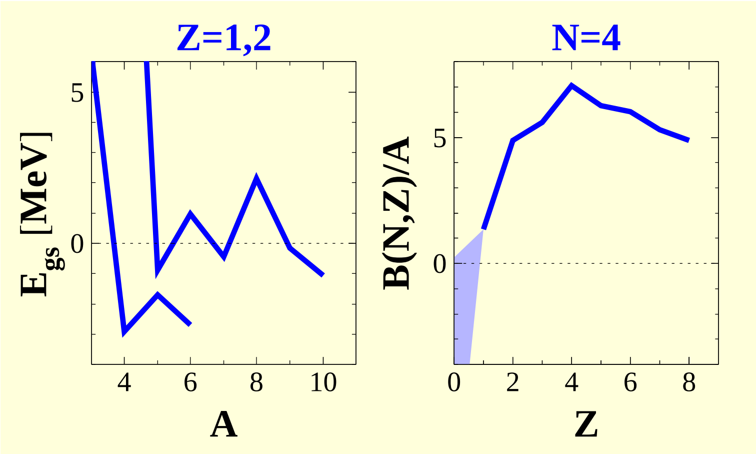
▶ models explore $V_{NN}(N>Z)$:

▷ $R_n(^{208}\text{Pb}) \leftrightarrow R_{star}$ ...

▷ better explore $V_{nn}(Z=0)$!!!

The landscape in 2001

▶ known masses & asymmetry :



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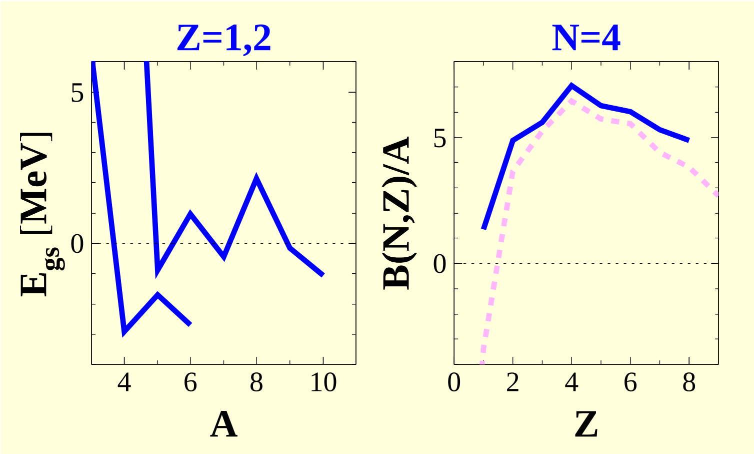

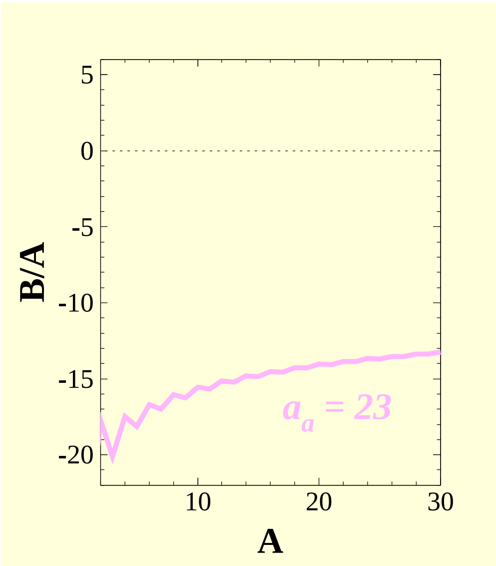

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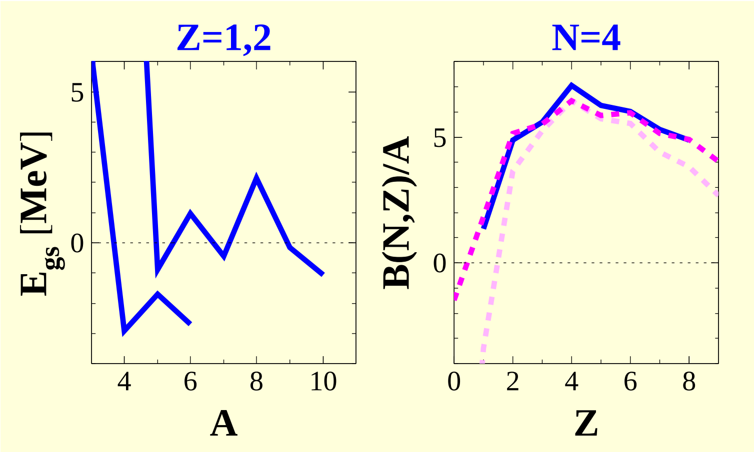

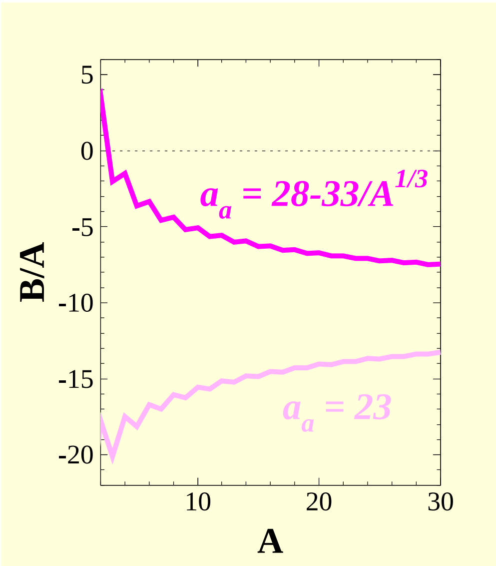

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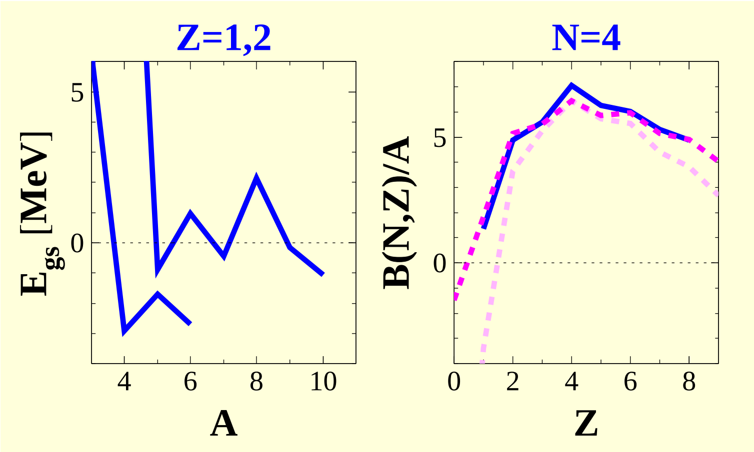
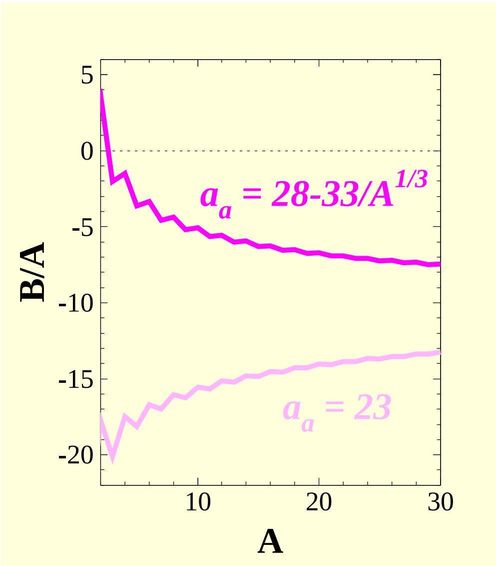
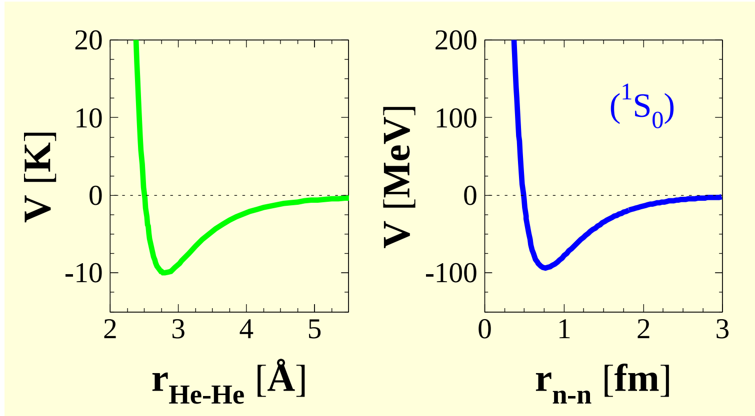




▶ few fermions bound ?



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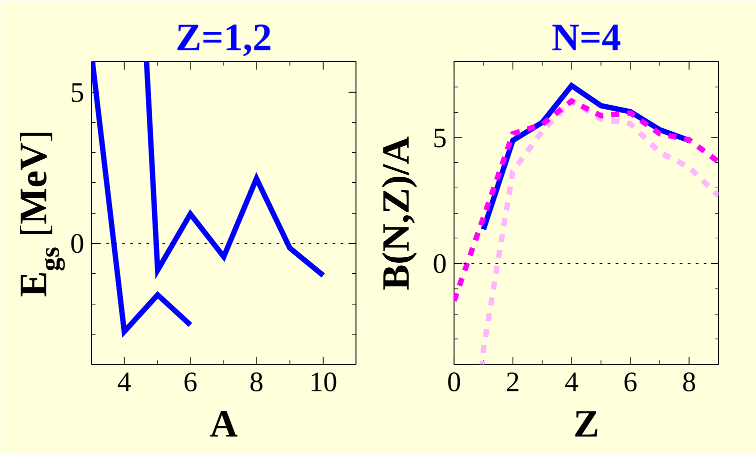

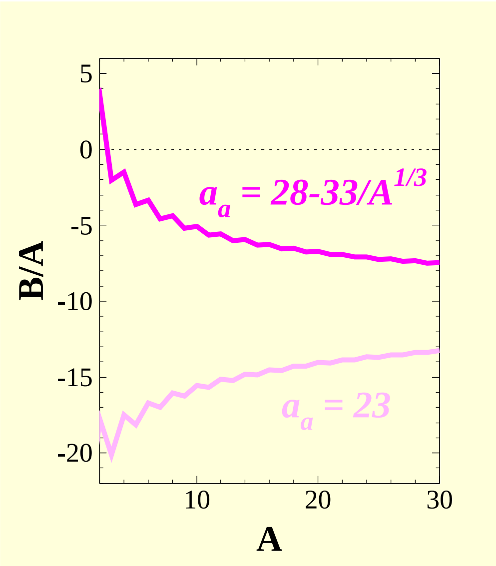

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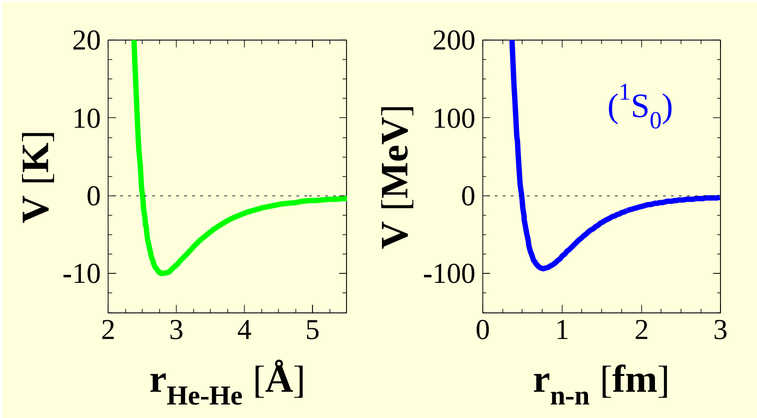
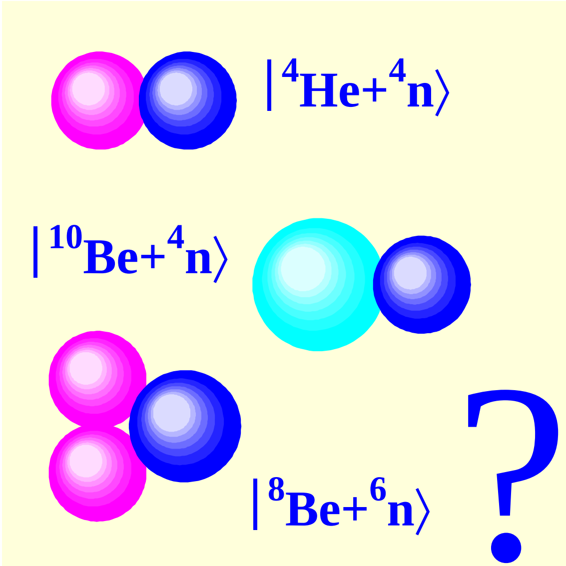


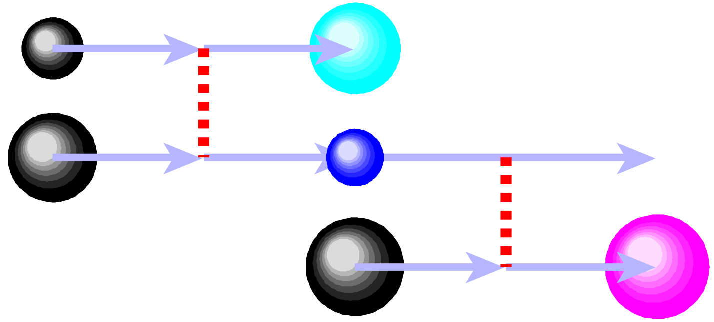


1960s-2000s : a long, unsuccessful quest

▶ 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 :

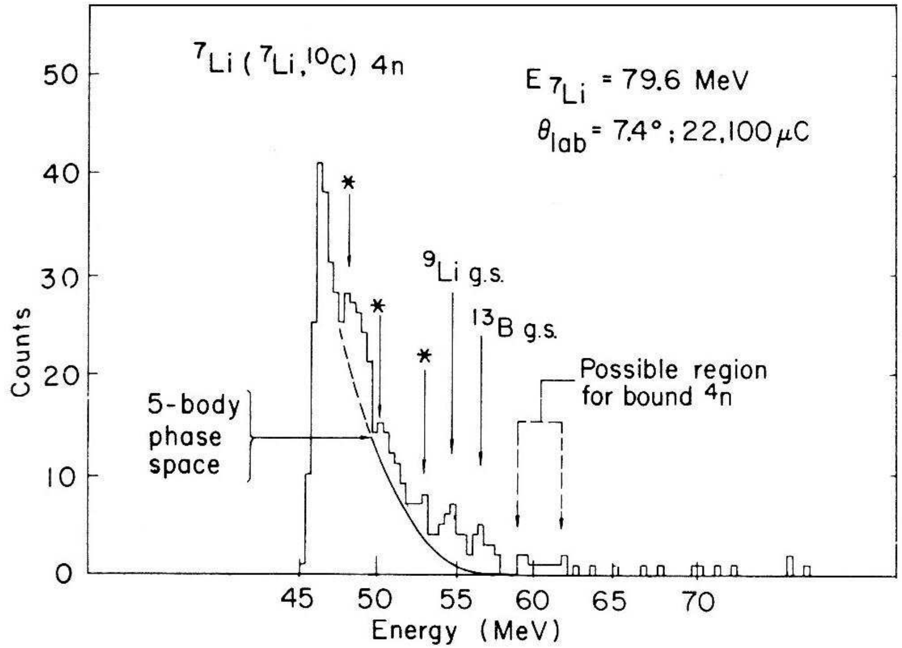
▷ ${}^{3}\mathrm{H}\,(\pi^-, \gamma)\,3n$

▷ ${}^{\{3,4\}}\mathrm{He}\,(\pi^-, \pi^+)\,\{3, 4\}n$

▶ multinucleon transfer :

▷ ${}^{7}\mathrm{Li} + {}^{11}\mathrm{B} \longrightarrow {}^{14}\mathrm{O} + 4n$

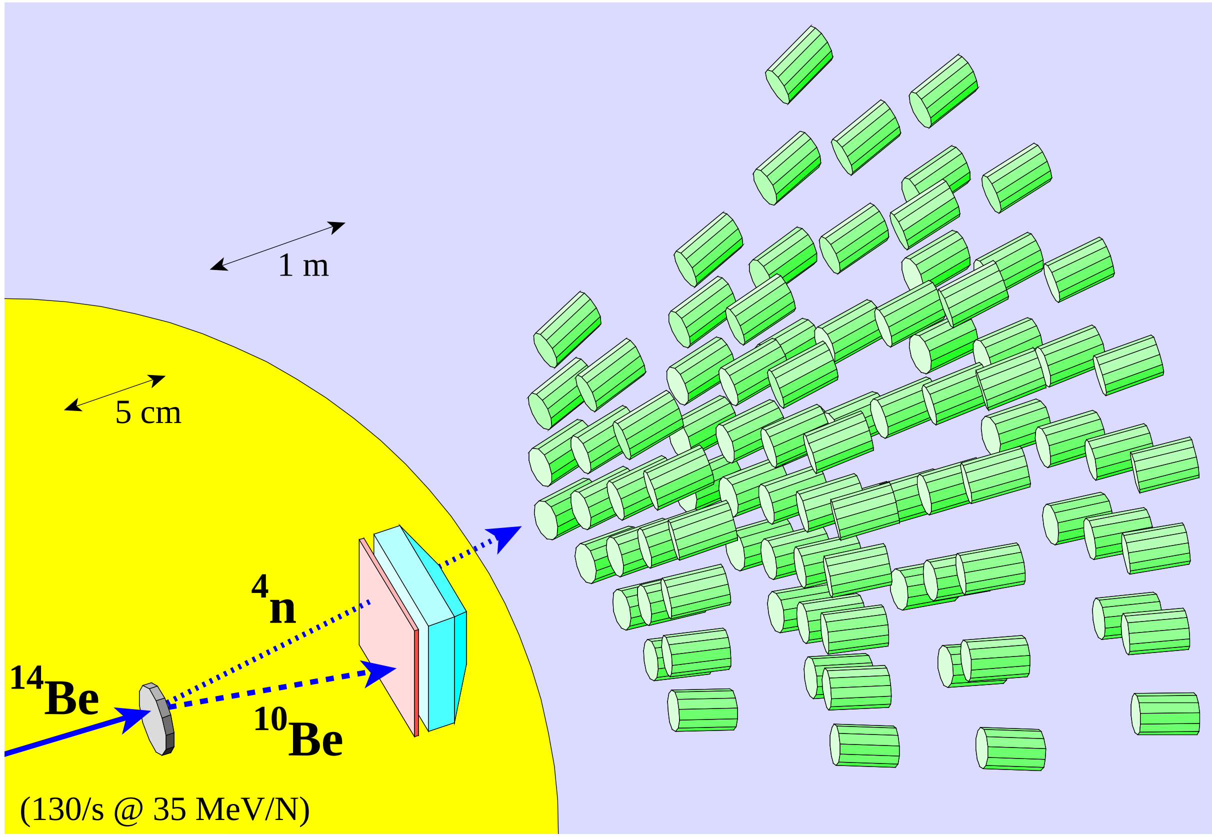
▷ ${}^{7}\mathrm{Li} + {}^{7}\mathrm{Li} \longrightarrow {}^{\{10,11\}}\mathrm{C} + \{4, 3\}n$



⇝ bcks + cross-sections …

The principle ...

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



▷ effective + clean

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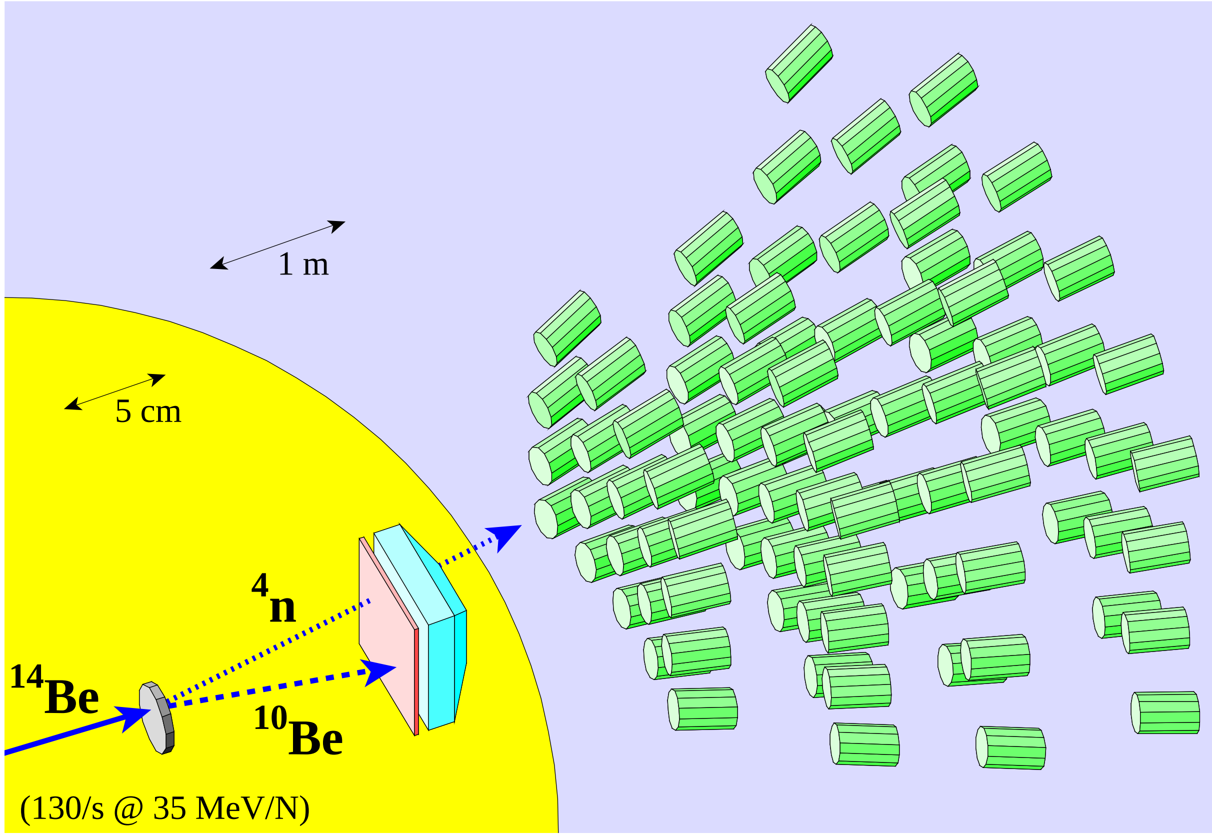
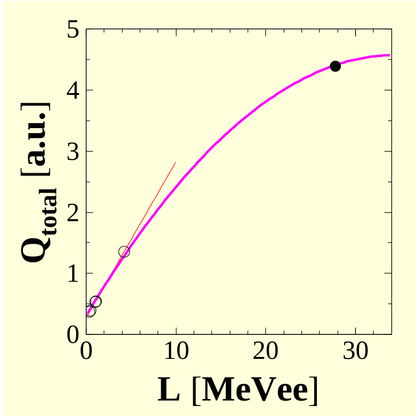
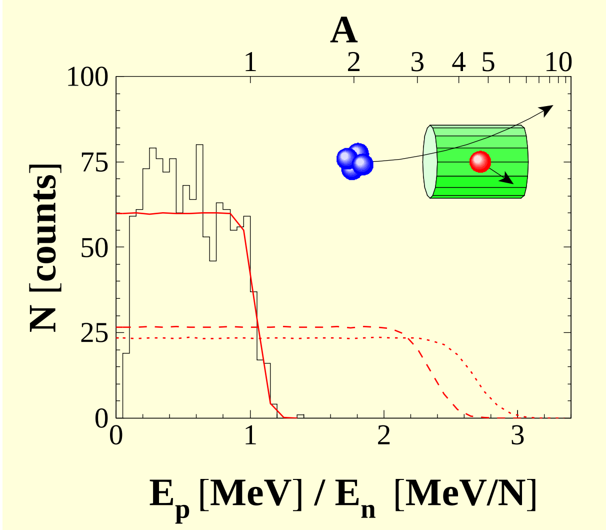


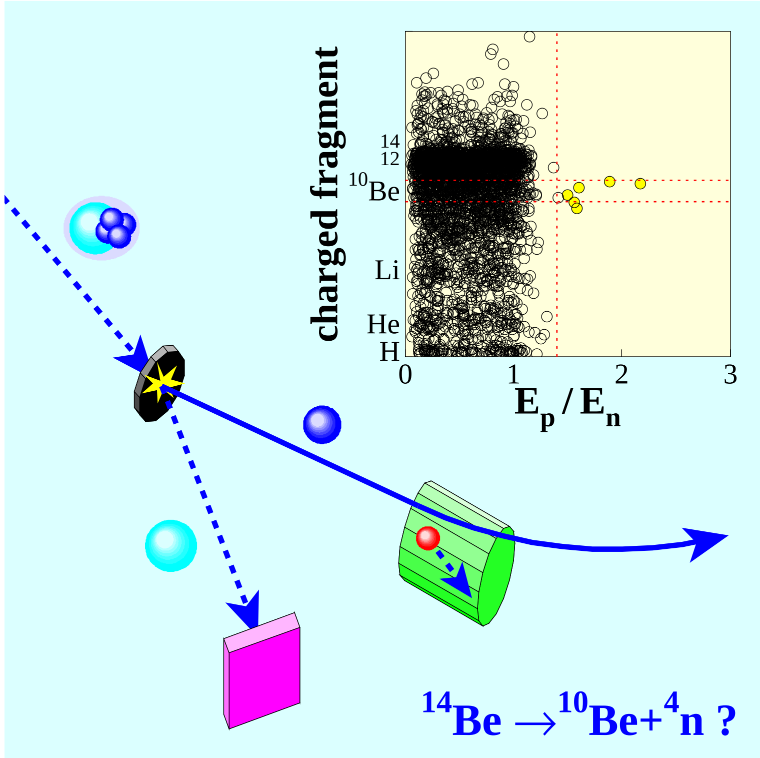




▷ effective + clean + sensitive !!!

▷ saturation (sensitive to low E_p) ...

… and the results



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

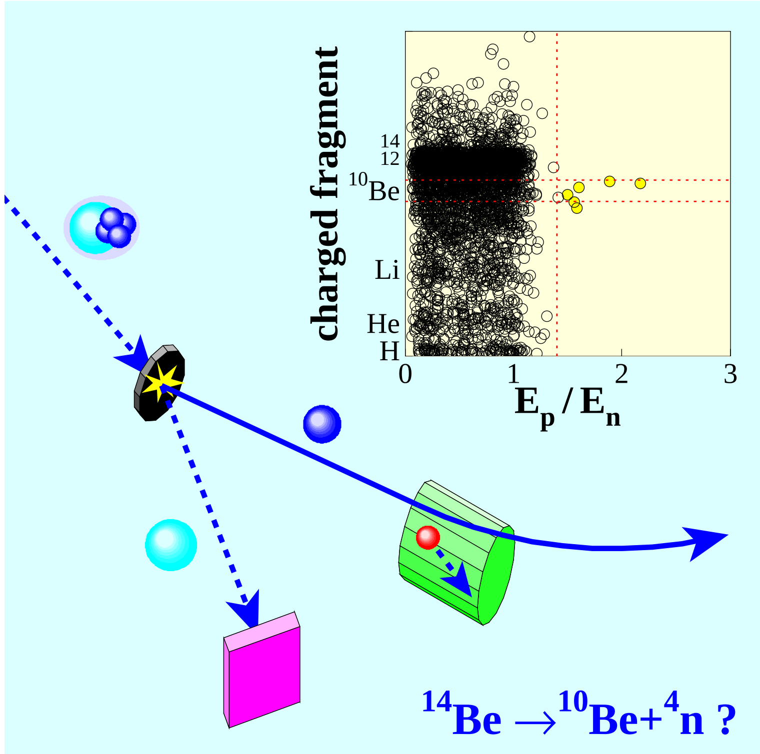
$$^{8}\text{He} \xrightarrow{(\text{C})} {}^{4}\text{He} + {}^{4}\text{n} \quad (\text{'02})$$

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

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

$$^{15}\text{B} \xrightarrow{(\text{C})} {}^{14}\text{Be}^{*} \longrightarrow {}^{4}\text{n} \quad (\text{'06})$$

… and the results



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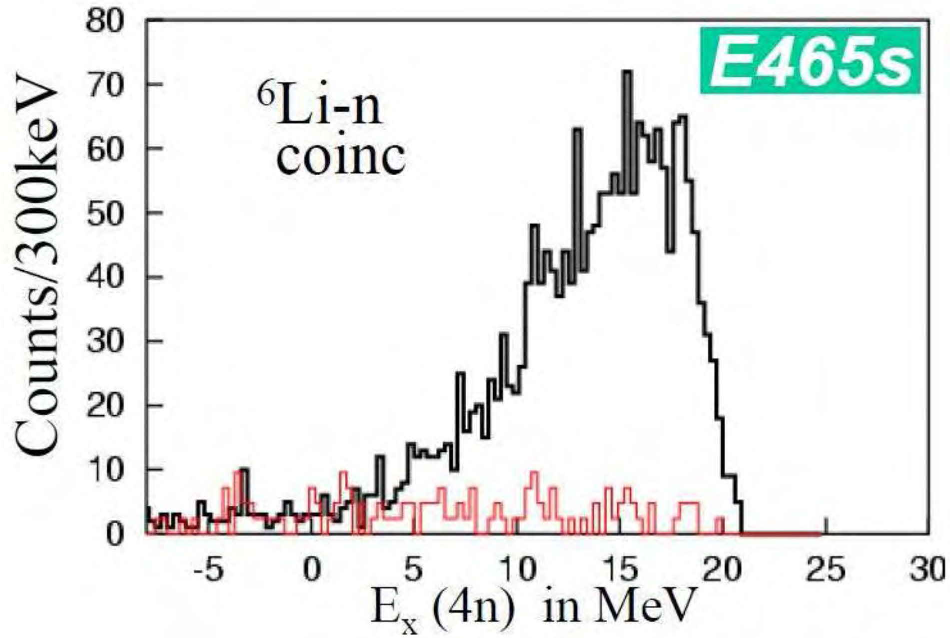
▶ transfer [Beaumel] :

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



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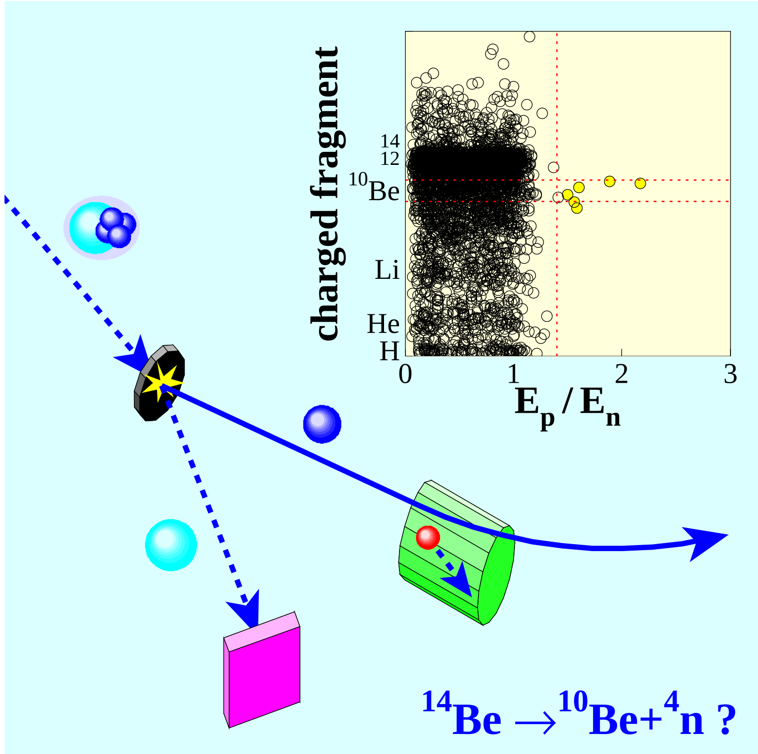

$^{14}\mathrm{Be} \xrightarrow{(C)} {}^{10}\mathrm{Be} + {}^{4}\mathrm{n}$ ('01,'02)

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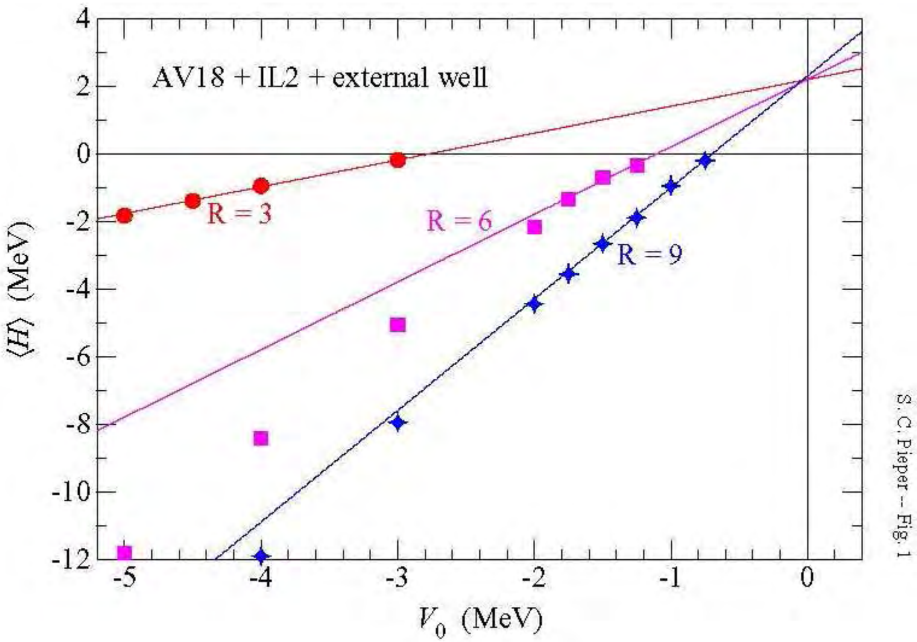
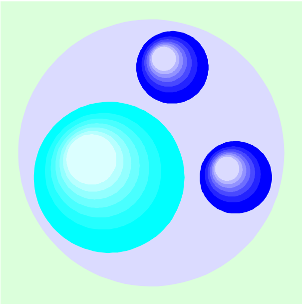
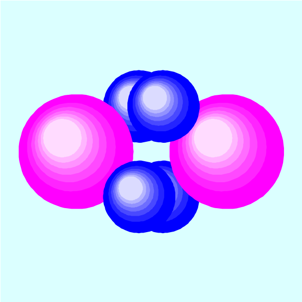


- "modern" calculations :
  - (^{4}n, p) scattering [Bertulani]
  - bound/resonance ? [Pieper, Carbonell]

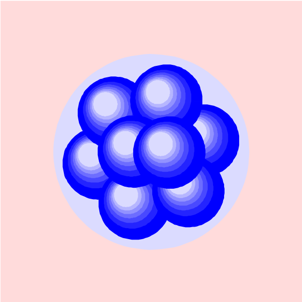
Summary & Conclusion



- understanding of cluster correlations [3α]
- very dilute matter: laboratory for NN interaction
- experimental input to three-body forces [V_{ijk}]
- where are the limits of the halo?



- completely different scales, concepts…
- completely analog molecular orbitals !
- deformation $\longrightarrow$ WF nodes $\longrightarrow$ clustering…
- how far can we push the analogy?



- many arguments are against…
- many hopes are for !
- neutron-rich beams provide new oportunities
- first "hints": new experiments and calculations…