Sub-barrier fusion of weakly bound nuclei:

Strong enhancement due to sequential fusion mechanism

- History
- Role of neutrons in fusion reactions
- Sequential fusion mechanism
- Huge enhancement in fusion of weakly bound nuclei
- Summary

Valery Zagrebaev, JINR, Dubna

History

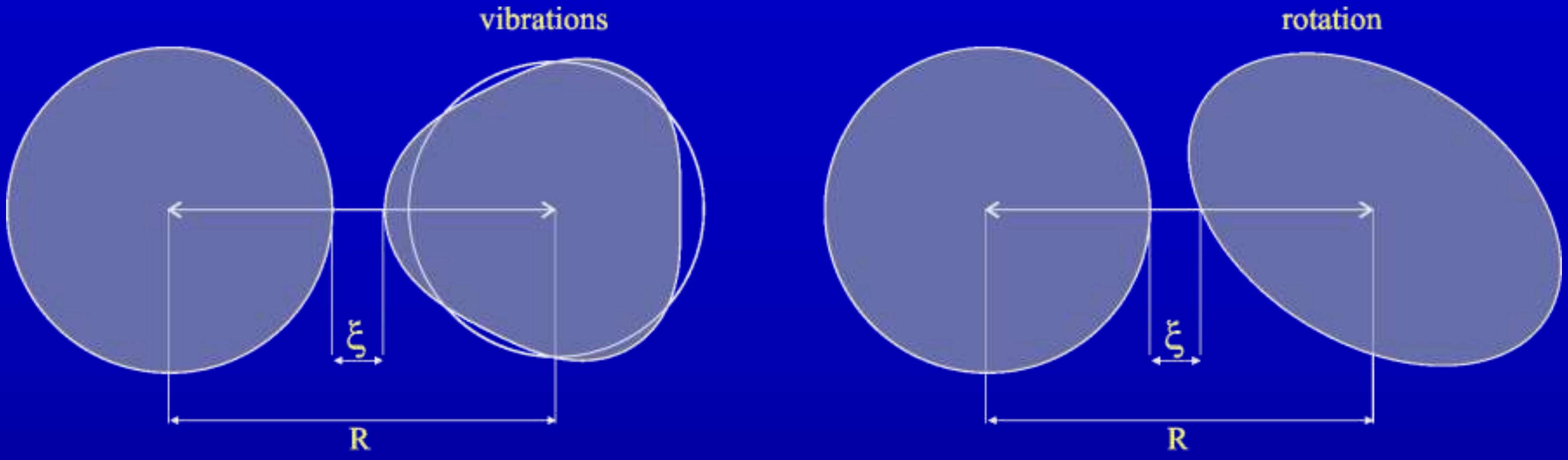
Theory:

- Takigawa and Sagawa, Phys.Lett. 1991: ^{11}Li+^{208}Pb, “halo, soft dipole mode” - enhancement
- Hussein et al, Phys.Rev. 1992: ^{11}Li+^{208}Pb, “break-up” – suppression
- Dasso and Vitturi, Phys.Rev. 1994: ^{11}Li+^{208}Pb, “both” – enhancement
- Hagino et al., Phys.Rev. 2000: ^{11}Be+^{208}Pb, “break-up” – enhancement
- Nakatsukasa et al., Fusion-2006: fusion suppression for neutron-halo nuclei

Experiment:

- Fomichev *et al.*, Z.Phys. 1995: ^{6}He+^{209}Bi, enhancement ?
- Kolata *et al.*, Phys.Rev. Lett. 1998: ^{6}He+^{209}Bi, enhancement !
- Trotta, Sida, Alamanos et al., Phys.Rev.Lett. 2000: ^{6}He+^{238}U, enhancement !
- Raabe et al., Nature 2004: ^{6}He+^{238}U, no fusion enhancement, only 2n-transfer
- Di Pietro et al., Phys. Rev. 2004: ^{6}He+^{64}Zn, no enhancement

Role of internal degrees of freedom



Distance between nuclear surfaces and, thus, the **Coulomb barrier** depend on vibrations and rotation:

$\mathbf{B} = \mathbf{B}(\beta_2,\beta_3)$, $\mathbf{B} = \mathbf{B}(\theta,\varphi)$ - multidimensional barriers.

Instead of one fixed barrier **B** we have a **“barrier distribution function” f(B)**.

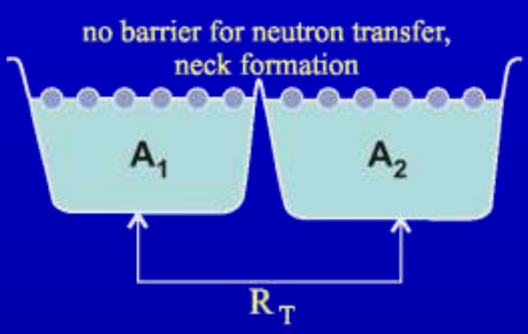
Barrier penetrability is $T(E,\ell)=\int f(B)P_0(B;E,\ell)dB.$

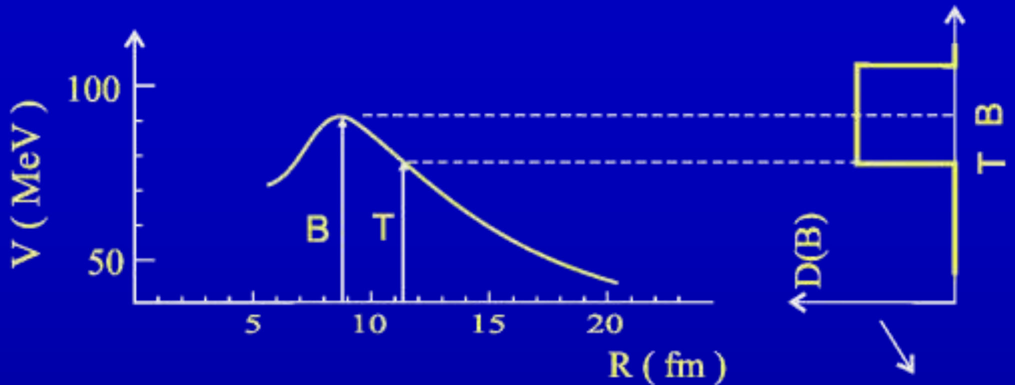
→ sub-barrier fusion enhancement

What is a role of neutrons in fusion process ?

Role of neutrons in sub-barrier fusion ?

H. Stelson, 1988





$$\sigma(E) = \pi R^2 \frac{(E-T)^2}{4(B-T)E}$$

N. Rowley, I.J. Thompson, and M.A. Nagarajan, PL, 1992
CC simulations:
→ $Q_n < 0$ - broad barrier distribution, necking
→ $Q_n > 0$ - “anti- necking” conditions

Ning Wang, Xizhen Wu, and Zhuxia Li, PRC, 2003
QMD calculations:
→ neutron excess plays a dominant role

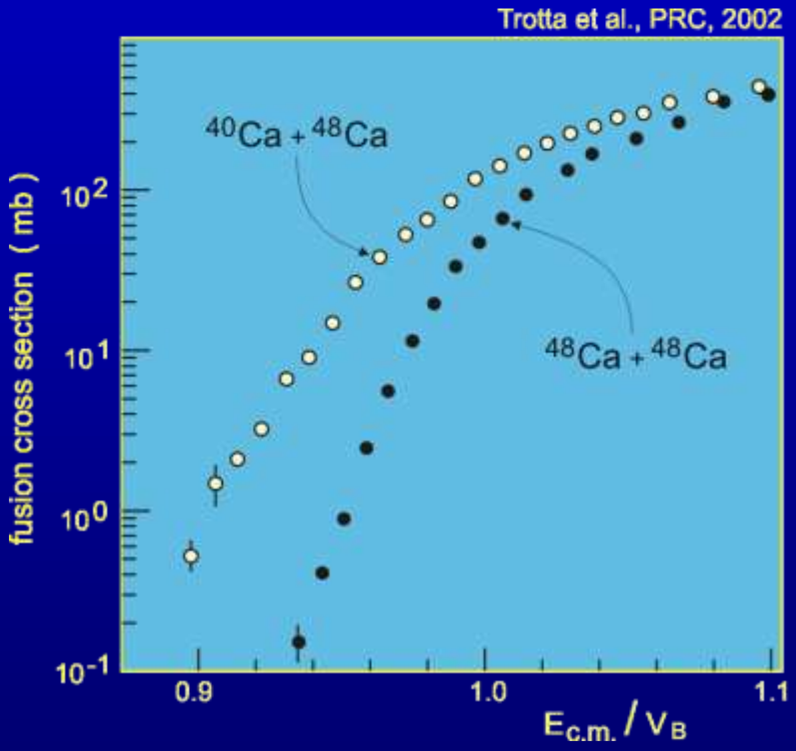
More neutrons - more probable fusion

$$\left.\frac{\sigma_{fus}(^{48}Ca + ^{48}Ca)}{\sigma_{fus}(^{40}Ca + ^{48}Ca)}\right|_{E<B} >> 1$$

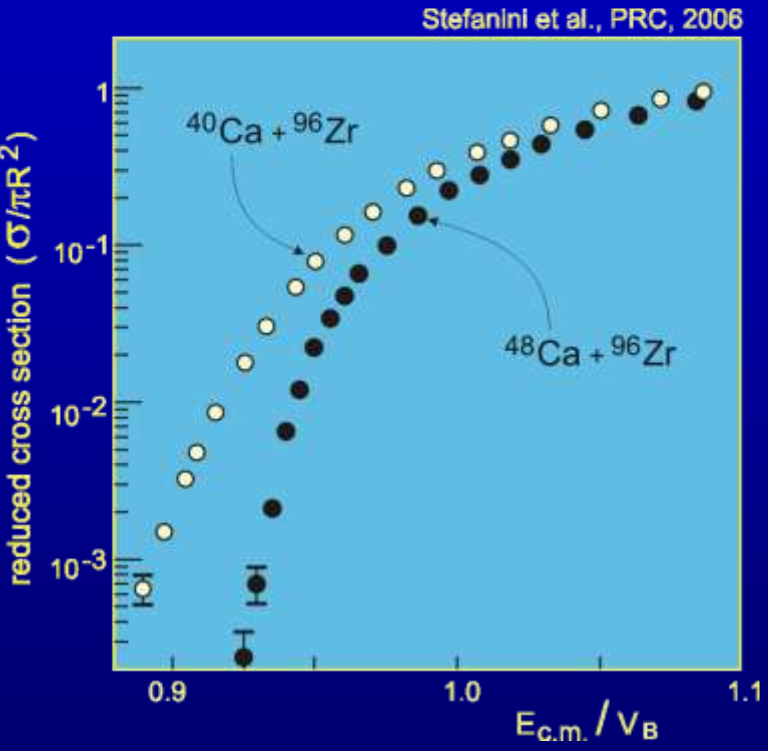
$$\left.\frac{\sigma_{fus}(^{48}Ca + ^{96}Zr)}{\sigma_{fus}(^{40}Ca + ^{96}Zr)}\right|_{E<B} >> 1$$

Wrong !

Neutron excess itself does not help nuclei to fuse !



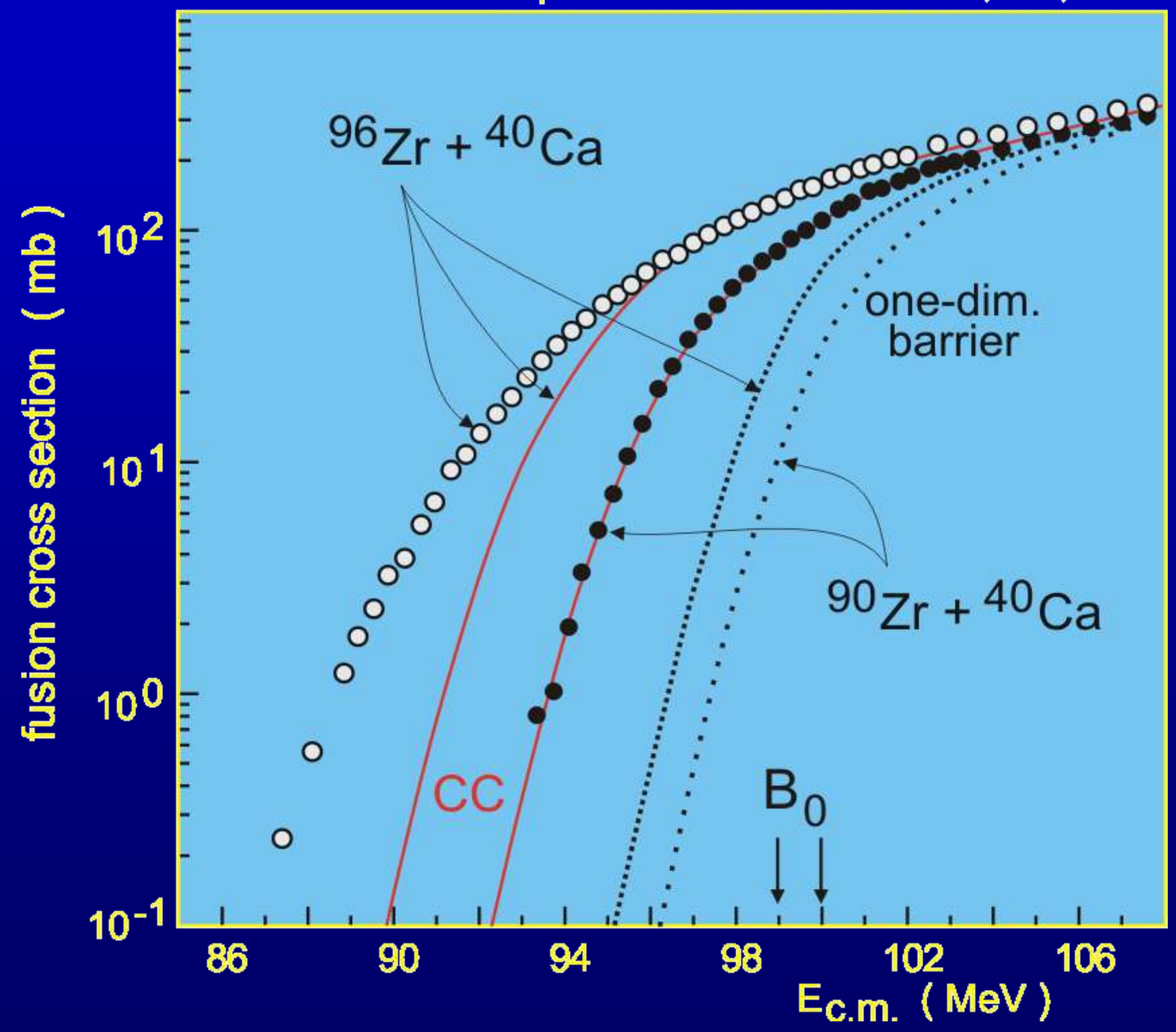
Trotta et al., PRC, 2002



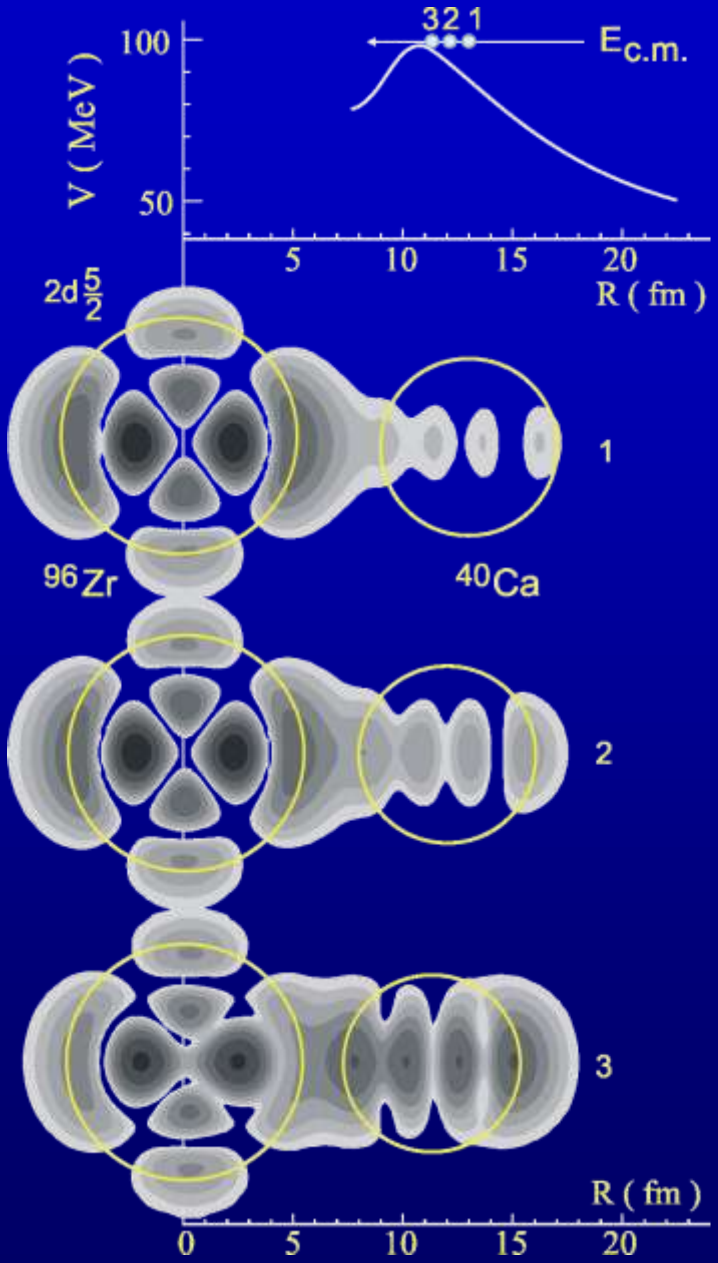
Stefanini et al., PRC, 2006

Lack of theory for fusion of some nuclei

experiment: Timmers et al., NP, 1998



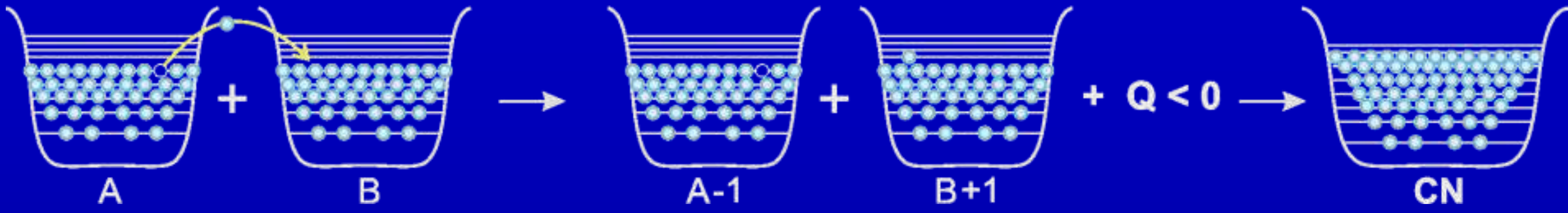
Solution of 3-body time-dependent Schrödinger equation



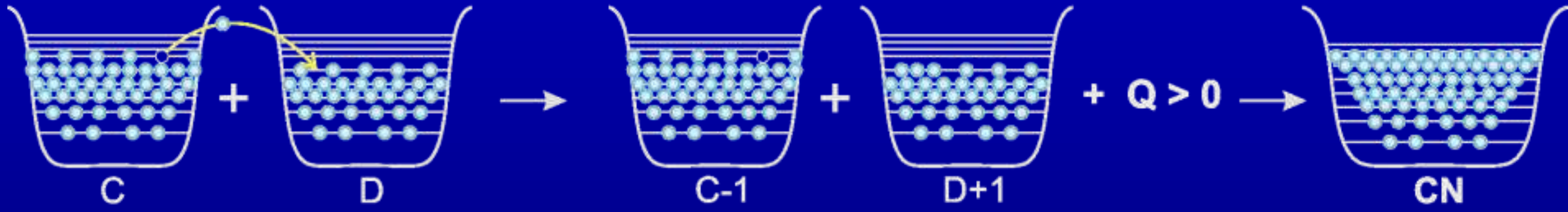
Wave functions of valence neutrons follow the two-center quasi-molecular states and **spread over the volumes of both nuclei** rather fast, before nuclei come in contact and even **before** they overcome the Coulomb barrier !

Gain due to positive Q-value of neutron rearrangement

In most combinations neutrons may be transferred only with negative Q-values



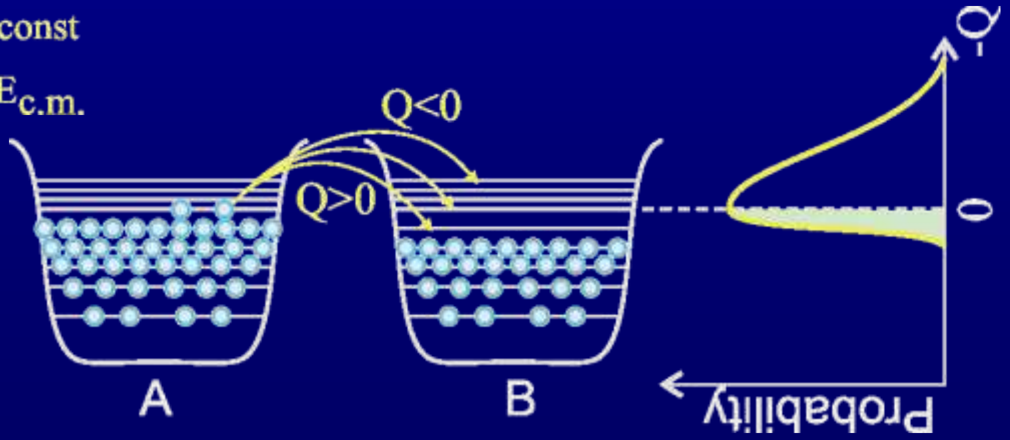
Nevertheless there are combinations with a chance for positive Q-value neutron transfer !



This gain in energy may go into the relative motion energy !

$$E_{c.m.} + M(A) + M(B) = E'_{c.m.} + M(A-1) + M(B+1) = \text{const}$$

if $[M(A-1)+M(B+1)] < [M(A)+M(B)]$ then $E'_{c.m.} > E_{c.m.}$



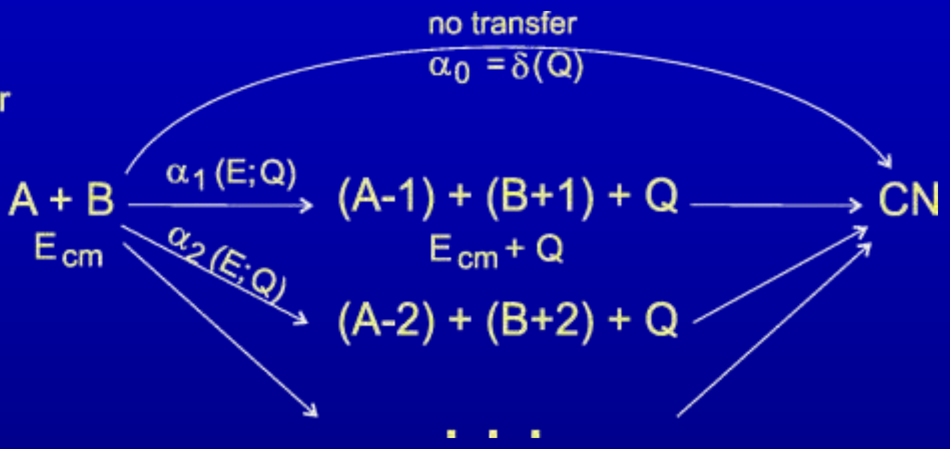
Sequential fusion process

$$\sigma_{fusion}(E) = \frac{\pi}{k^2} \sum (2\ell+1)\cdot T(\ell,E)$$

$$T(\ell,E) = \int_0^\infty f(B)\, P_0\,(B;\ell,E)\, dB$$

barrier distribution function

subsequent neutron transfer
and "sequential fusion":



$$T(\ell,E) = \int_0^\infty f(B) \int_{-E}^{Q_0(k)} \frac{1}{N}\left[\,\delta(Q) + \sum_{k\geq1} \alpha_k\,(E;\ell,Q)\right]\, P_0\,(B;\ell,E+Q)\, dQ\, dB$$

$Q_0(k)$ is the Q-value of g.s. transfer

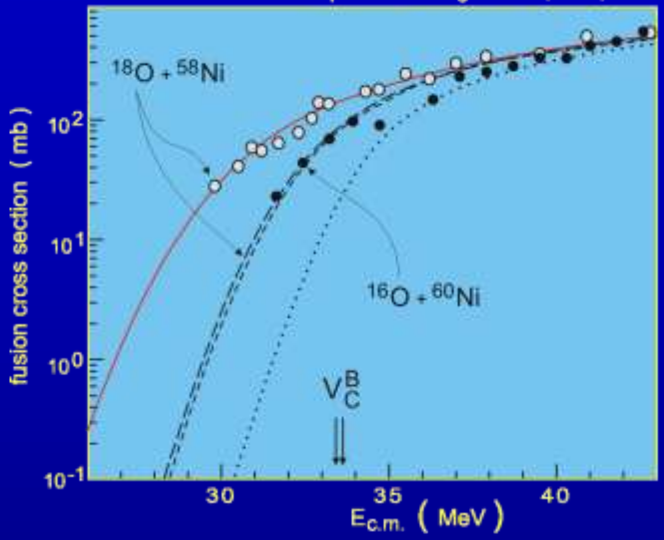
probability for transfer of k neutrons: $\alpha_k\,(E;\ell,Q) = N_k\, e^{-C[Q-Q_{opt}]^2}\, e^{-2\gamma[D(E,\ell)\,-\,D_0]}$

$D(E,\ell)$ is the distance of closest approach, and $D_0 = d_0\,(A^{1/3} + B^{1/3})$, $d_0 \approx 1.4$ fm

$\gamma = \gamma(\varepsilon_1) + \gamma(\varepsilon_2) + \ldots + \gamma(\varepsilon_k)$, $\gamma(\varepsilon) = \sqrt{2\mu\varepsilon/\hbar^2}$

Fusion enhancement for stable neutron rich nuclei

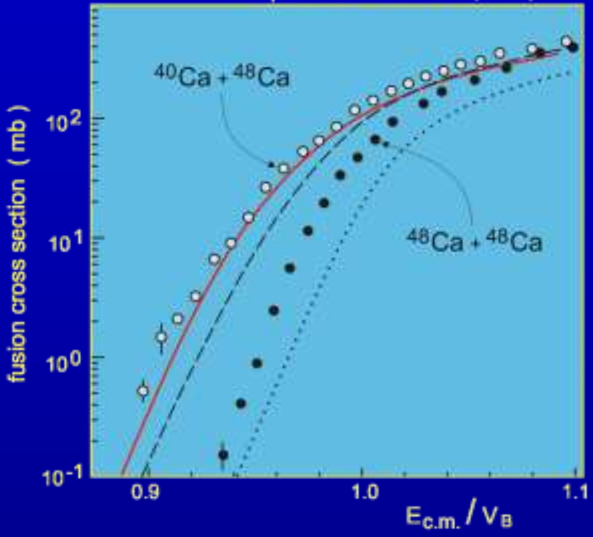
experiment: Borges et al., PRC, 1992



$^{18}O + ^{58}Ni \rightarrow ^{16}O + ^{60}Ni \rightarrow CN$

$Q_{gg}(2n) = +8.2$ MeV

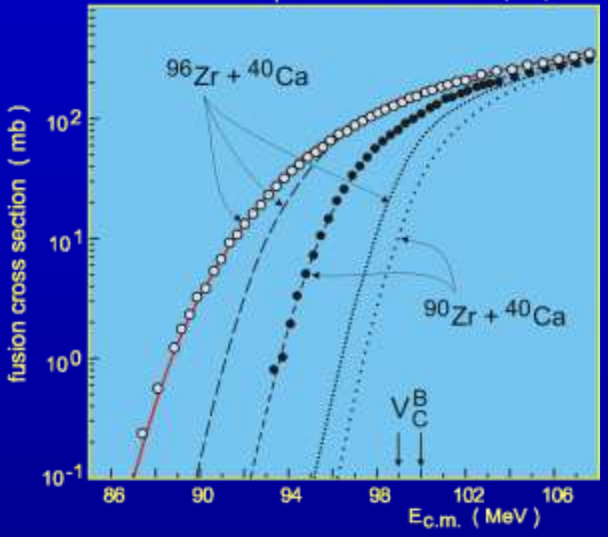
experiment: Trotta et al., PRC, 2002



$^{48}Ca + ^{40}Ca \rightarrow ^{44}Ca + ^{44}Ca \rightarrow CN$

$Q_{gg}(4n) = +3.9$ MeV

experiment: Timmers et al., NP, 1998



$^{96}Zr + ^{40}Ca \rightarrow ^{92}Zr + ^{44}Ca \rightarrow CN$

$Q_{gg}(4n) = +9.6$ MeV

Idea of "sequential fusion" mechanism with intermediate neutron rearrangement seems to work !

Test for the “neutron rearrangement” mechanism in sub-barrier fusion reactions

Stable nuclei:

$^{40}\mathrm{Ca} + {}^{124}\mathrm{Sn} \rightarrow < {}^{44}\mathrm{Ca} + {}^{120}\mathrm{Sn} + 9.5\ \mathrm{MeV} > \rightarrow {}^{164}\mathrm{Yb}$

$^{48}\mathrm{Ca} + {}^{116}\mathrm{Sn} \rightarrow < \quad \text{all } Q_n^{\text{trans}} < 0 \quad > \rightarrow {}^{164}\mathrm{Yb}$

$^{14}\mathrm{C} + {}^{40}\mathrm{Ca} \rightarrow < {}^{12}\mathrm{C} + {}^{42}\mathrm{Ca} + 6.7\ \mathrm{MeV} > \rightarrow {}^{54}\mathrm{Fe}$

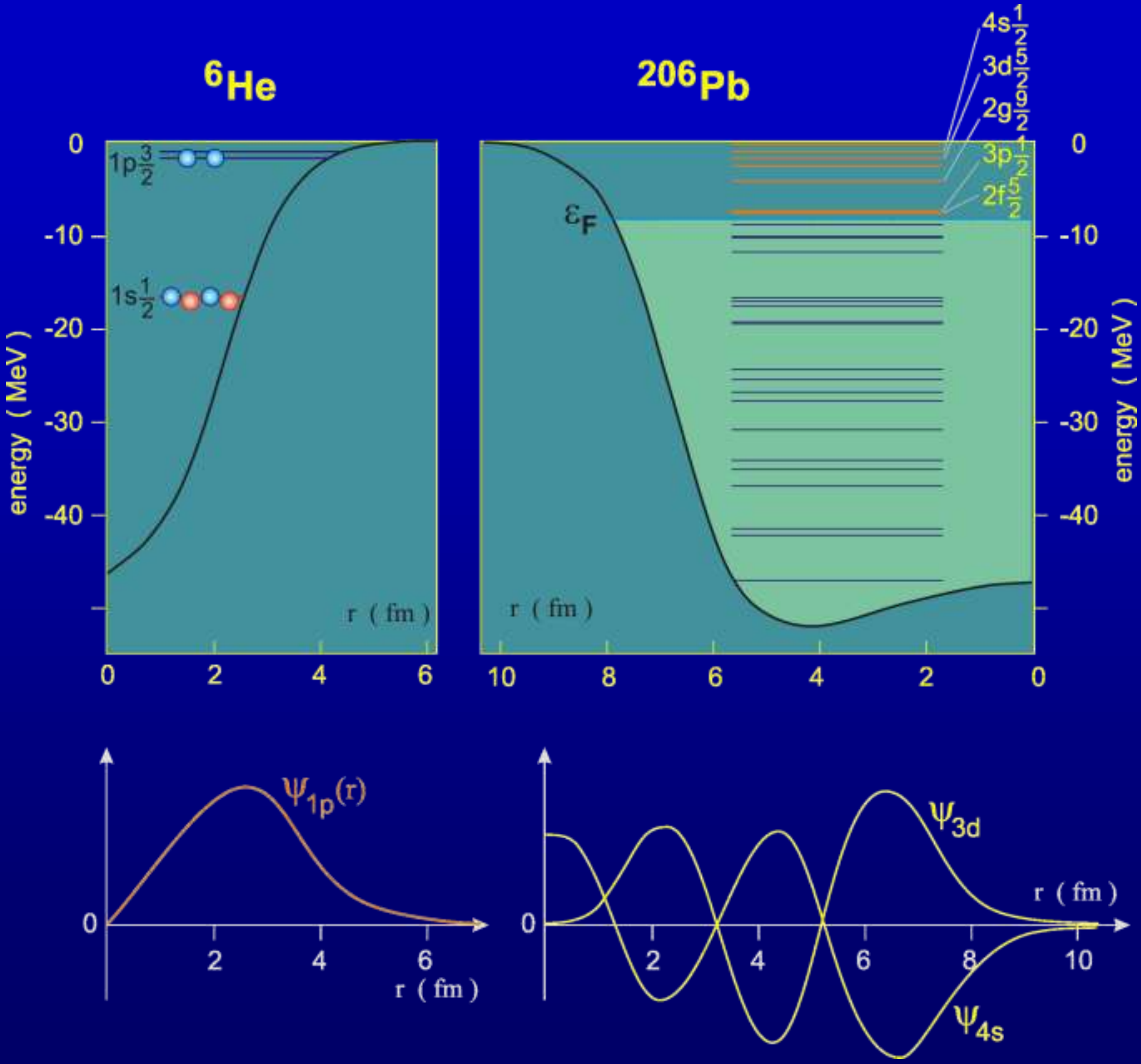
$^{12}\mathrm{C} + {}^{42}\mathrm{Ca} \rightarrow < \quad \text{all } Q_n^{\text{trans}} < 0 \quad > \rightarrow {}^{54}\mathrm{Fe}$

Weakly bound nuclei:

$^{6}\mathrm{He} + {}^{206}\mathrm{Pb} \rightarrow < {}^{4}\mathrm{He} + {}^{208}\mathrm{Pb} + 13.1\ \mathrm{MeV} > \rightarrow {}^{212}\mathrm{Po}$

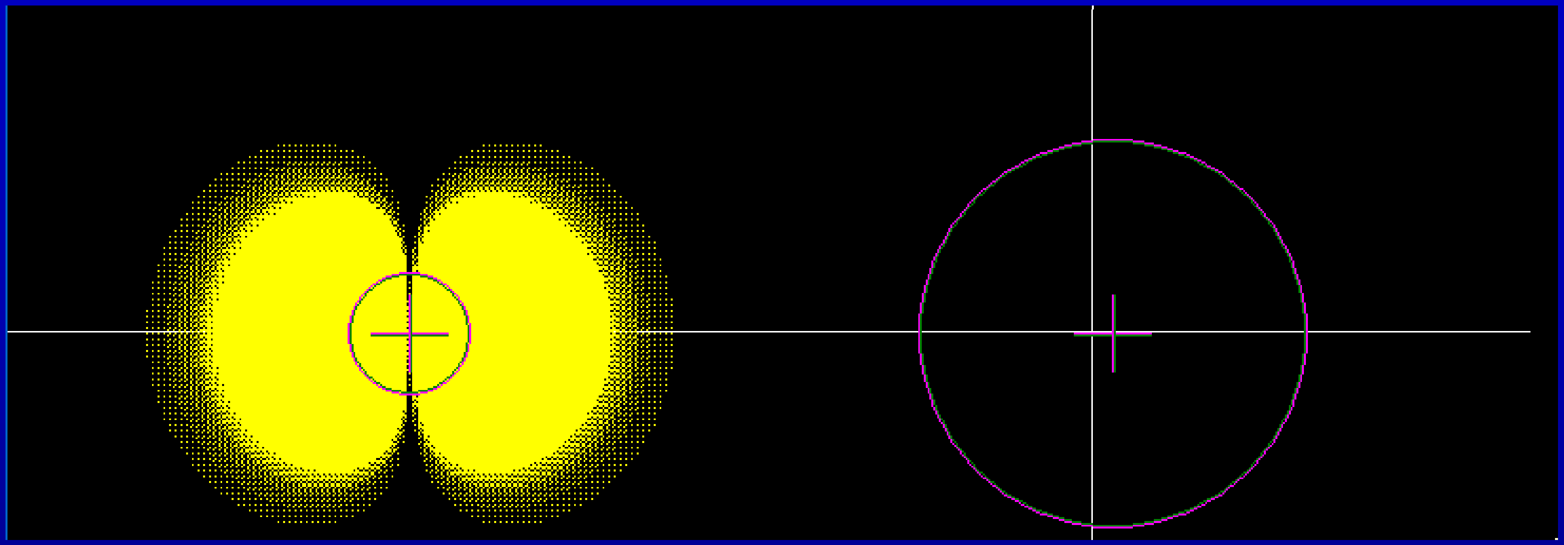
$^{4}\mathrm{He} + {}^{208}\mathrm{Pb} \rightarrow < \quad \text{all } Q_n^{\text{trans}} < 0 \quad > \rightarrow {}^{212}\mathrm{Po}$

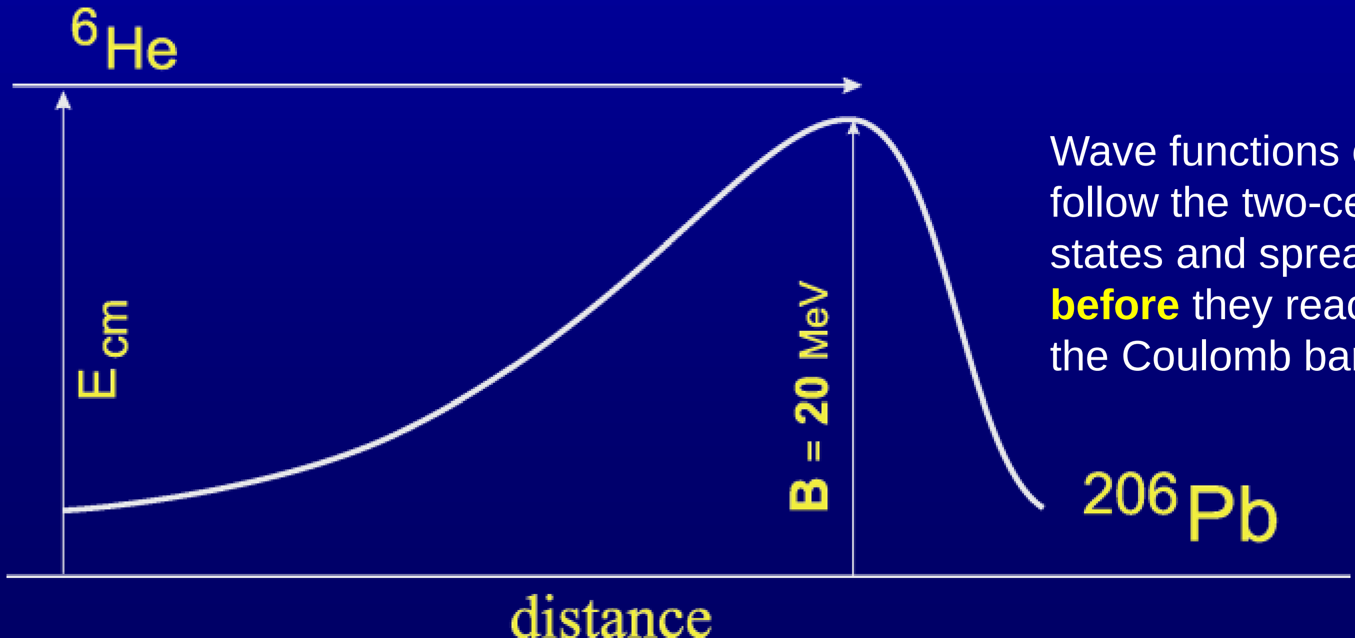
^{6}He + ^{206}Pb



6He
206Pb
4s1/2
3d5/2
2g9/2
3p1/2
2f5/2
1p3/2
1s1/2
εF
energy (MeV)
0
-10
-20
-30
-40
r (fm)
0
2
4
6
10
8
6
4
2
0
ψ1p(r)
ψ3d
ψ4s
r (fm)
0
2
4
6
8
10

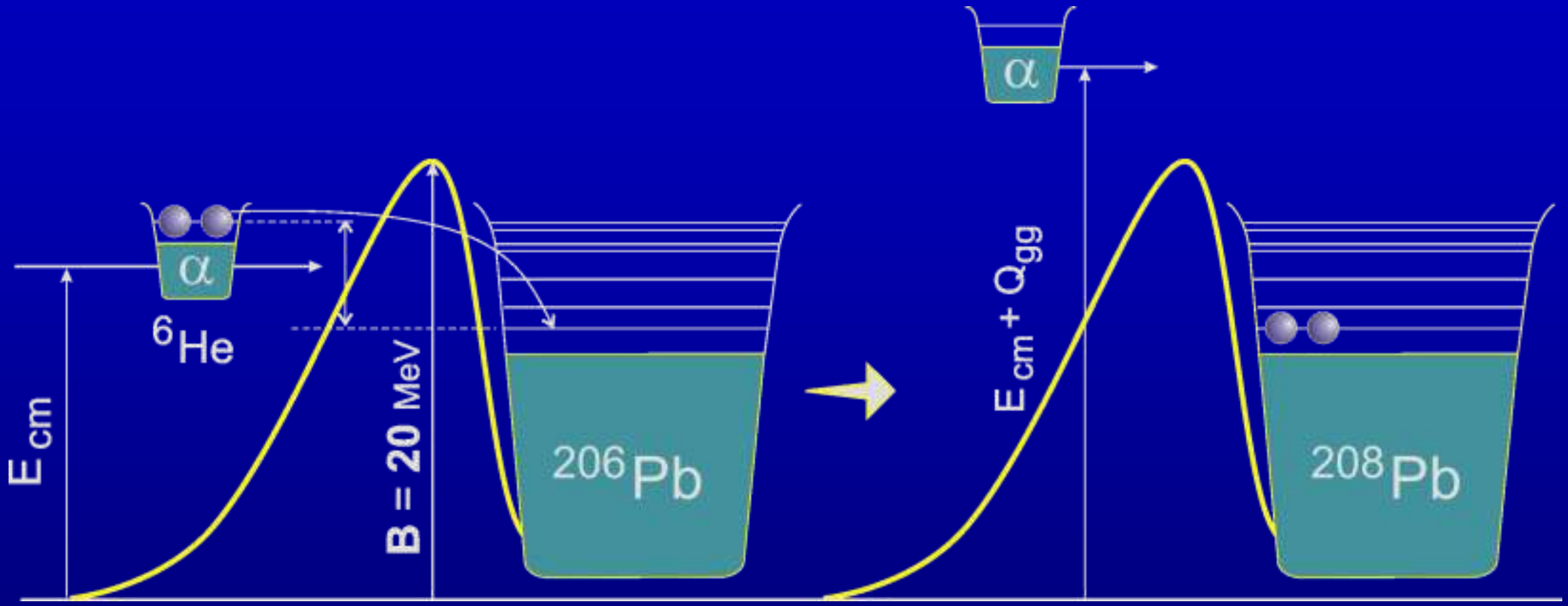
Time-dependent analysis of ^{6}He + ^{206}Pb collision





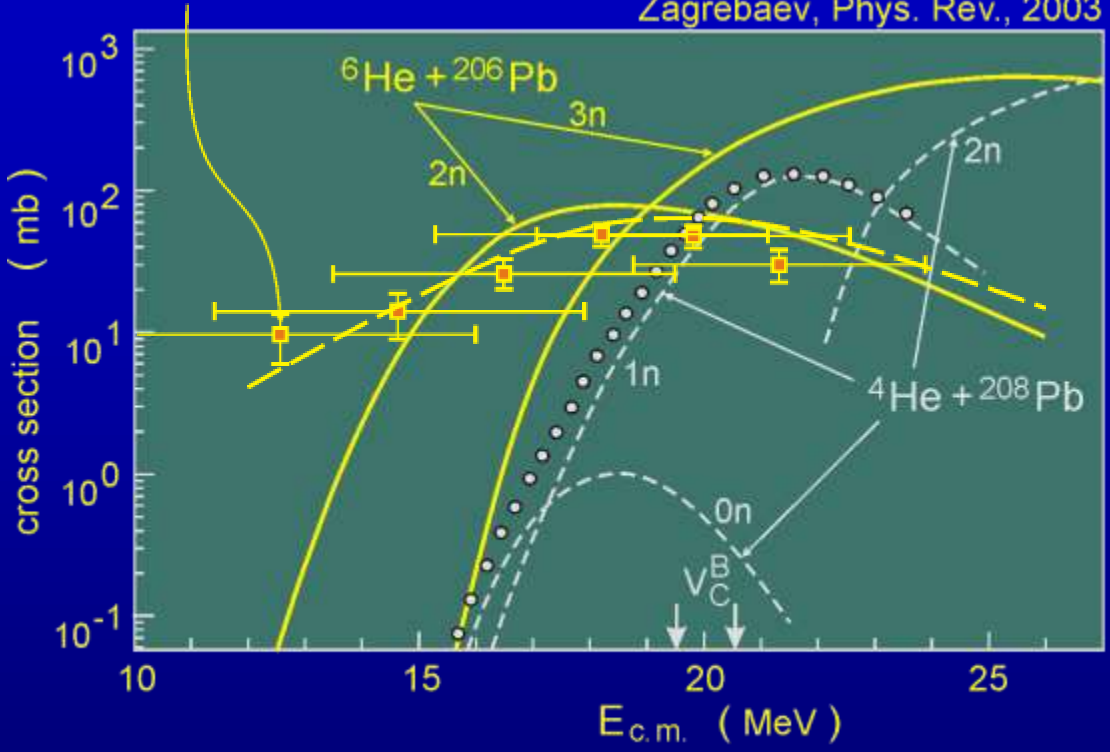
Wave functions of valence neutrons follow the two-center molecular states and spread over both nuclei **before** they reach and overcome the Coulomb barrier !

Schematic picture for sequential fusion of ^{6}He



Huge enhancement in deep sub-barrier fusion of weakly bound nuclei

Penionzhkevich, Zagrebaev, Lukyanov and Kalpakchieva,
Phys. Rev. Lett, **96**,2006



Zagrebaev, Phys. Rev., 2003

$$\left.\frac{\sigma(^6\mathrm{He}+{}^{206}\mathrm{Pb}\to{}^{212}\mathrm{Po})}{\sigma(^4\mathrm{He}+{}^{208}\mathrm{Pb}\to{}^{212}\mathrm{Po})}\right|_{E_{c.m.}=15\ \mathrm{MeV}} = 10^3$$

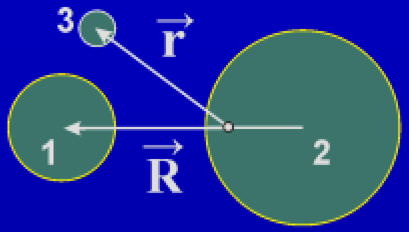
(same "temperature")

Raabe et al., Nature, 2004

^{6}He+^{238}U:

No fusion enhancement !

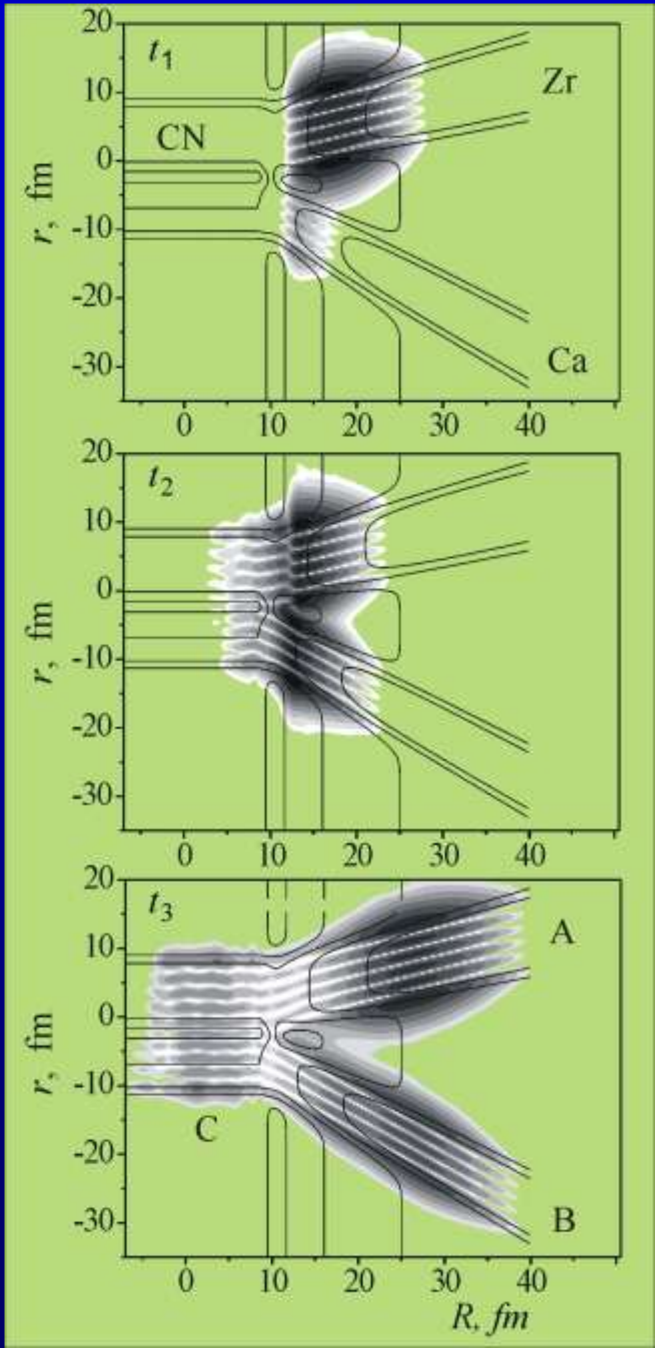
Time-dependent Scrodinger equation



$$i\hbar \frac{\partial \Psi}{\partial t} = \left[-\frac{\hbar^2}{2m_3}\Delta_{\mathbf{r}} + V(\mathbf{r},\mathbf{R}(t)) \right] \Psi(\mathbf{r},t,\mathbf{R}(t))$$

$$i\hbar \frac{\partial \Psi}{\partial t} = \left[-\frac{\hbar^2}{2m_3}\Delta_{\mathbf{r}} - \frac{\hbar^2}{2M}\frac{\partial^2}{\partial R^2} + V_{12}(R) + V_n(\mathbf{r},R) \right] \Psi(\mathbf{r},R,t)$$

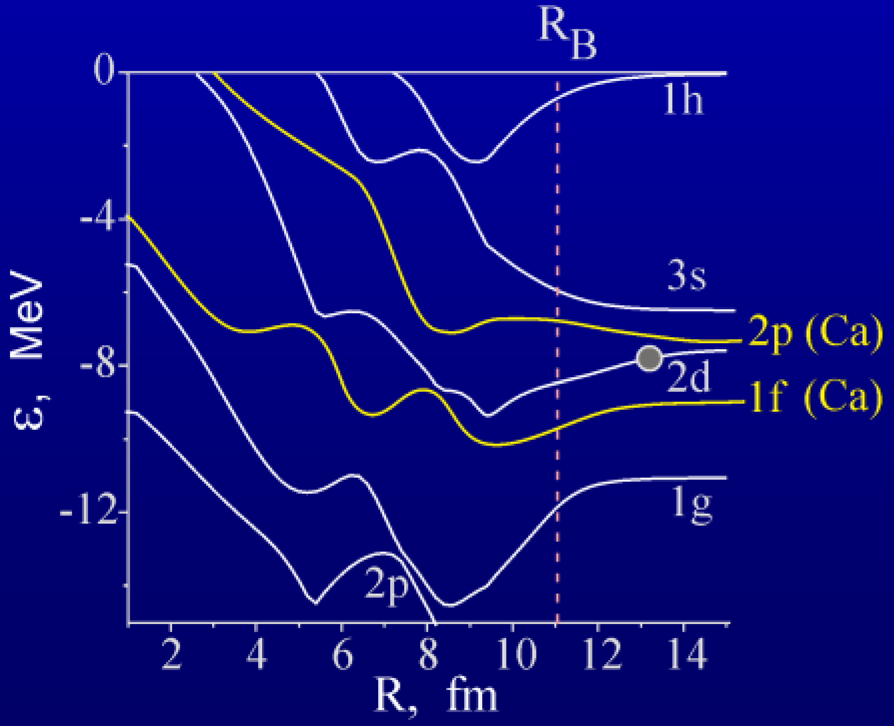
$$T(t,E) = \int_{-\infty}^{R_B} dR \int d^3\mathbf{r} \; |\Psi(\mathbf{r},R,t)|^2$$



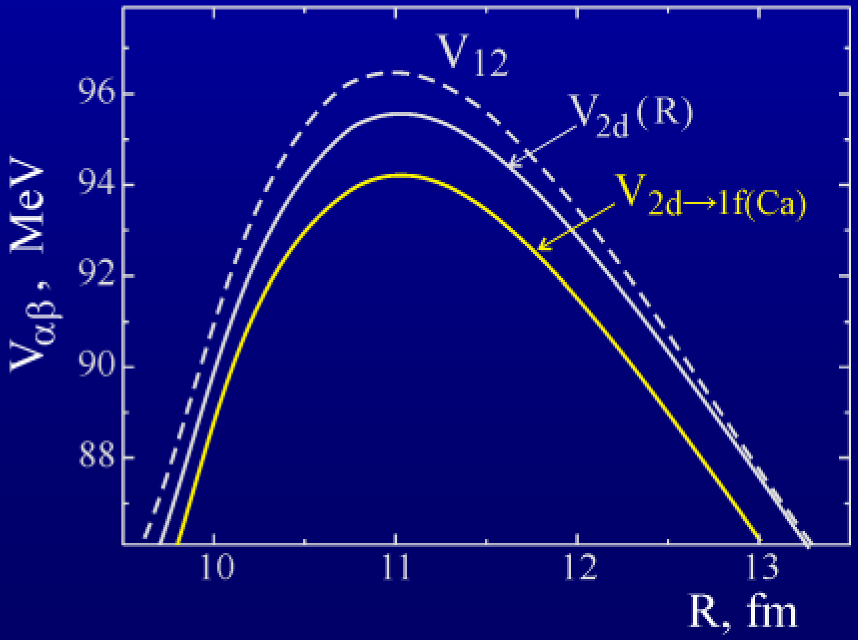
Two mechanisms of fusion enhancement due to neutron exchange

$$V_{\alpha\beta}(R) = V_{12}(R) + \varepsilon_\beta(R) - \varepsilon_\alpha(\infty)$$

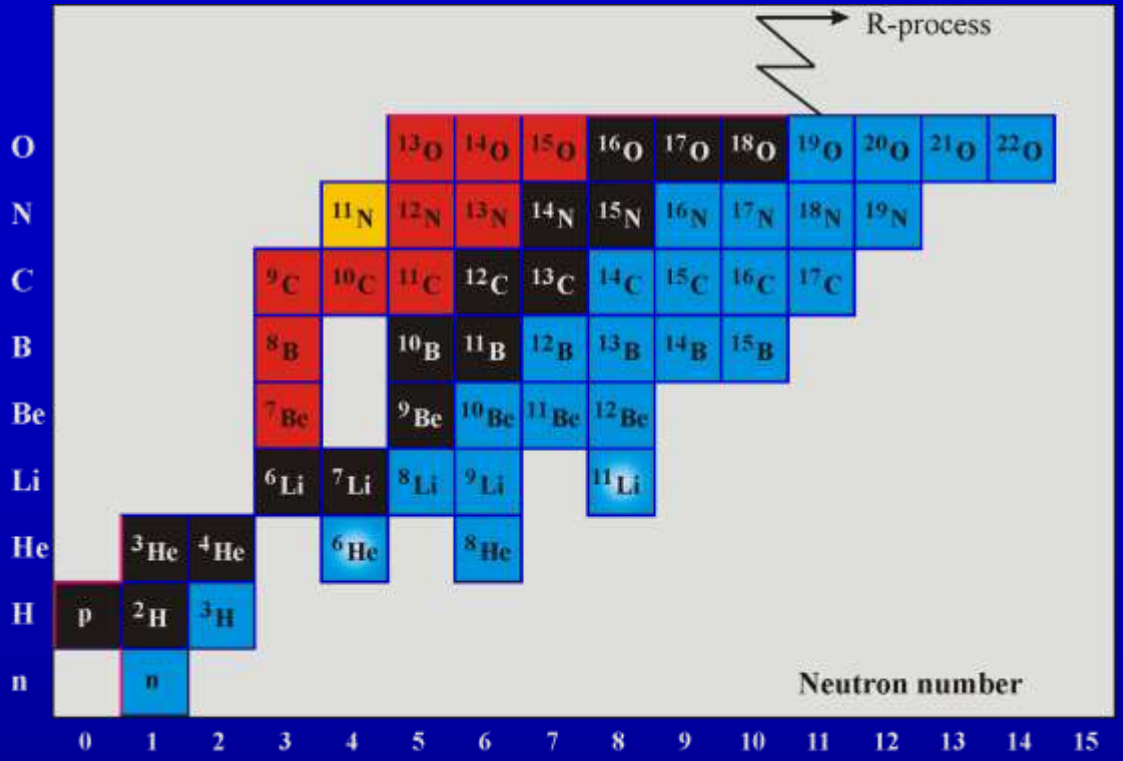
single particle levels in the ^{96}Zr + ^{40}Ca system



nucleus-nucleus potential energy of ^{40}Ca + ^{96}Zr



Nucleosynthesis



some chains :

$^{1}H(n,\gamma)^{2}H(n,\gamma)^{3}H(d,n)^{4}He(^{3}H,\gamma)^{7}Li(n,\gamma)^{8}Li,$

$^{8}Li(^{4}He,n)^{11}B(n,g)^{12}B(\beta\,\bar{\nu})^{12}C(n,\gamma)^{13}C(n,\gamma)^{14}C$

$^{14}C(^{4}He,\gamma)^{18}O$ plays the major role in heavy element production (Malanay and Fowler, Astroph. Journal, 1988)

$^{14}C + ^{4}He \rightarrow <$ all $Q_{n}^{trans} < 0$ $> \rightarrow ^{18}O$

$^{12}C + ^{6}He \rightarrow < ^{12}C + ^{4}He + 12$ MeV $> \rightarrow ^{18}O$

$$\left.\frac{\sigma_{fus}(\,^{6}He + ^{12}C)}{\sigma_{fus}(\,^{4}He + ^{14}C)}\right|_{E<B} >> 1$$

Conclusion

- “Sequential fusion” mechanism plays an important role
- Rearrangement of neutrons with positive Q-value significantly increases sub-barrier fusion probability
- Huge enhancement in fusion of weakly bound nuclei is revealed
- New experiments on sub-barrier fusion of light weakly bound nuclei - like $^{12}C(^{6}He,n\gamma)^{17}O$ - are to be performed
- Scenario of primordial nucleosynthesis may be revised