

Fission and more with HFB-Gogny

Beginnings and recent

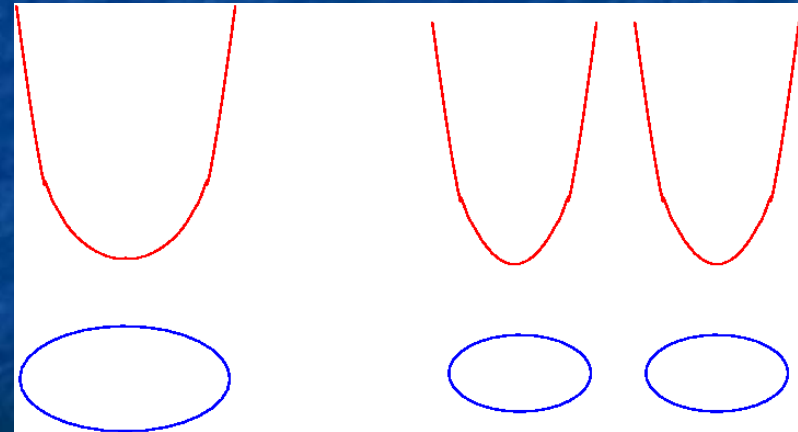
Two-center bases for HFB

Usual HO bases very efficient for HFB with D1 interaction :

$$v(1,2) \cong \sum_{\mu \leq N} \hat{\phi}_{\mu}(1) f_{\mu}^{[v]}(2)$$

“Développement
de Gogny”

However HO bases with reasonable size are not adapted to two-nucleus configurations



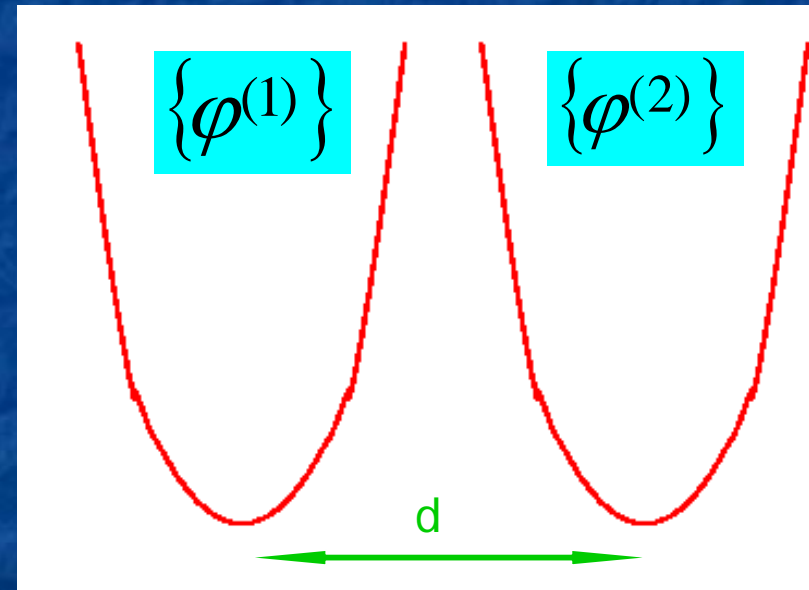
Eigenfunctions of two-center HO potential not convenient for HFB :

- ❑ they are hyper-geometric functions
- ❑ “développement de Gogny” not applicable

Another way : $\{\varphi^{(1)}\} \oplus \{\varphi^{(2)}\}$

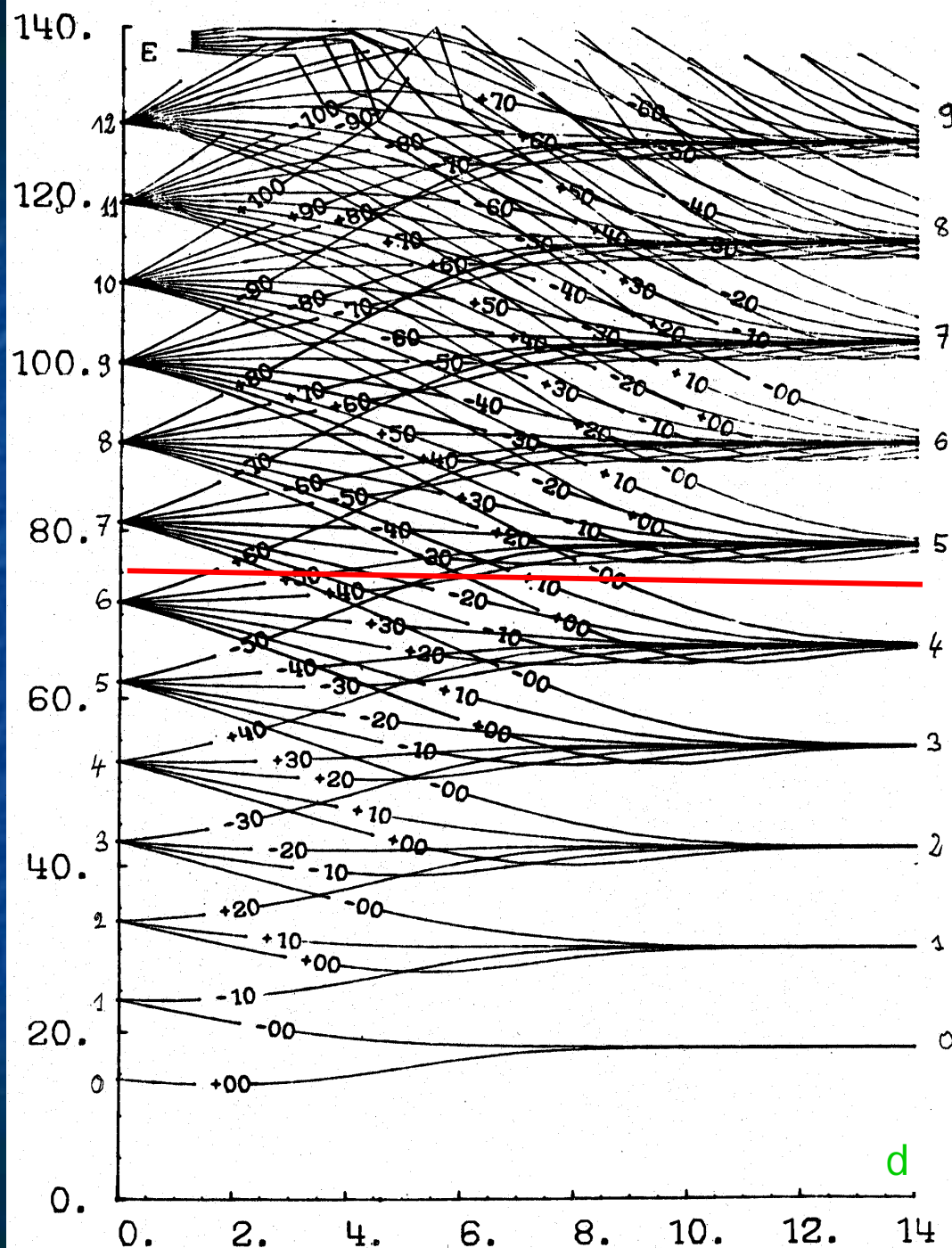
Non-orthogonal (overcomplete) basis

Orthogonalisation and elimination of
redundant vectors from diagonalisation
of T^+T and TT^+ with $T_{ij} = (\varphi_i^{(1)}, \varphi_j^{(2)})$



Much more accurate and fast than Schmidt orthogonalisation !

More important: “le développement de Gogny” can be employed

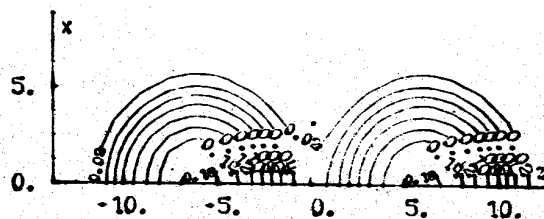


Axial symmetry

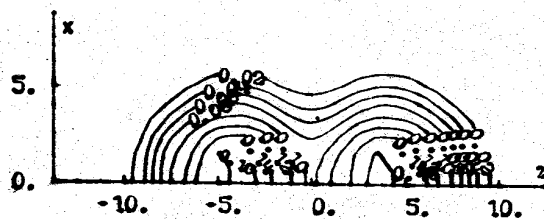
Single part. energies
in two-center HO pot

Twice 10 HO shells
~ 1900 nucleon states

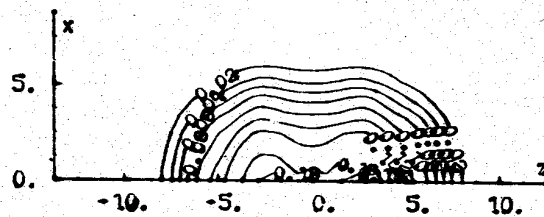
$A=2 \times 112$
 $D=12.00$
 $Q=7952.$



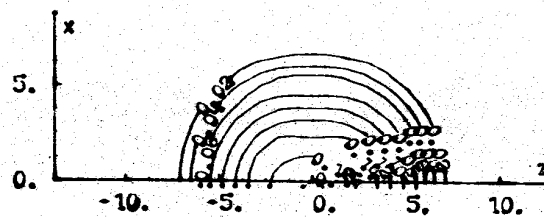
$A=2 \times 112$
 $D=8.00$
 $Q=3633.$



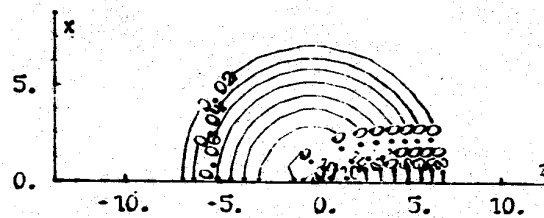
$A=2 \times 112$
 $D=4.00$
 $Q=1445.$



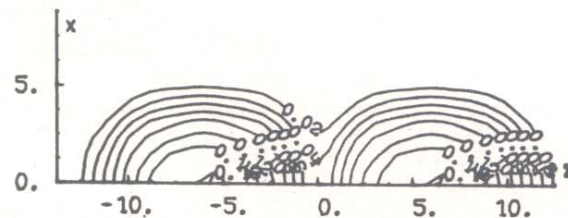
$A=2 \times 112$
 $D=2.00$
 $Q=305.$



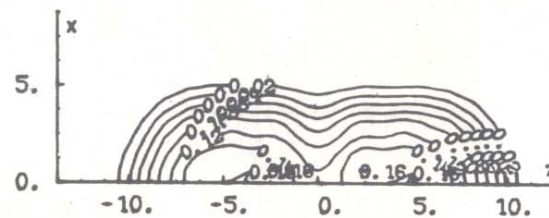
$A=2 \times 112$
 $D=0.00$
 $Q=0.$



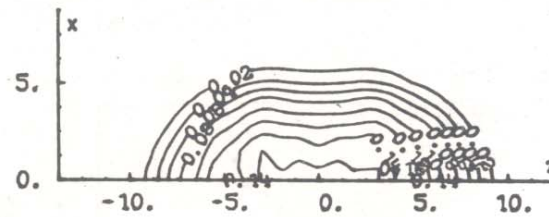
$A=2 \times 112$
 $D=12.00$
 $Q=8727.$



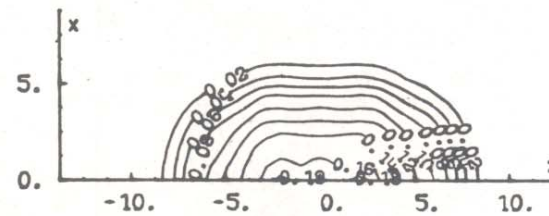
$A=2 \times 112$
 $D=8.00$
 $Q=4654.$



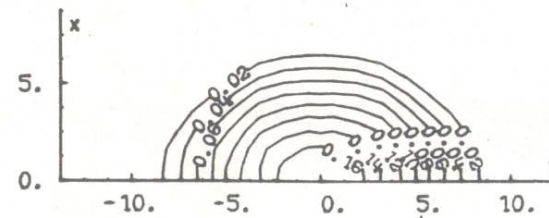
$A=2 \times 112$
 $D=4.00$
 $Q=2092.$



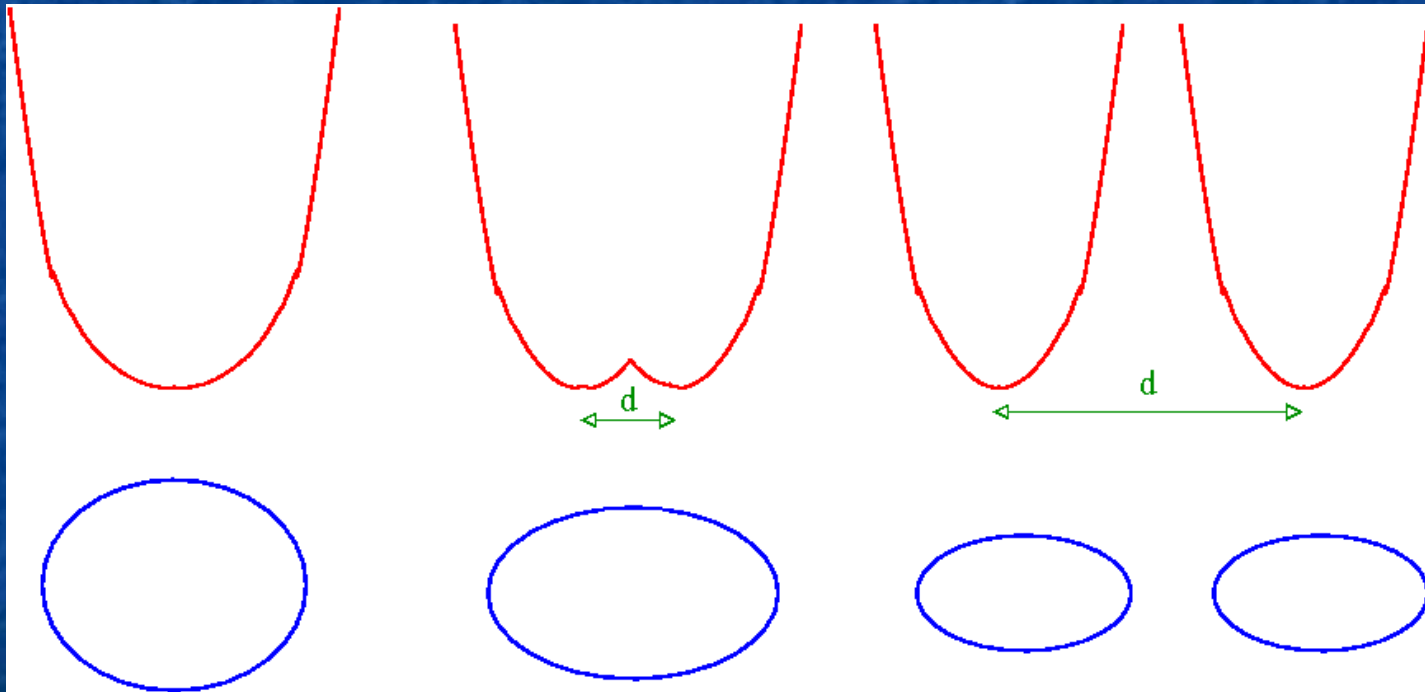
$A=2 \times 112$
 $D=2.00$
 $Q=1522.$



$A=2 \times 112$
 $D=0.00$
 $Q=900.$



With this method, two-center bases are competitive
not only for two-nucleus configurations
but also for one-nucleus very deformed states



despite one additional parameter to be optimised : d

$^{12}\text{C} + ^{12}\text{C}$ and molecular states

- Sharp close resonances in $^{12}\text{C} + ^{12}\text{C}$ excitation functions near Coulomb barrier
- Long-lived “molecule” ?
- Also in a couple of other systems ($^{12}\text{C} + ^{16}\text{O}$, $^{14}\text{N} + ^{14}\text{N}$)
- Various interpretations not successful
- Description with HFB
- **One problem:** spurious center of mass energy and potential energy of asymptotic states

- Removal of spurious center of mass (CM) energy in HFB:
minimisation of

$$\hat{H}' = \hat{H} - \frac{\hat{P}^2}{2AM}$$

➤ One-body and Two-body corrections

- At large distance R

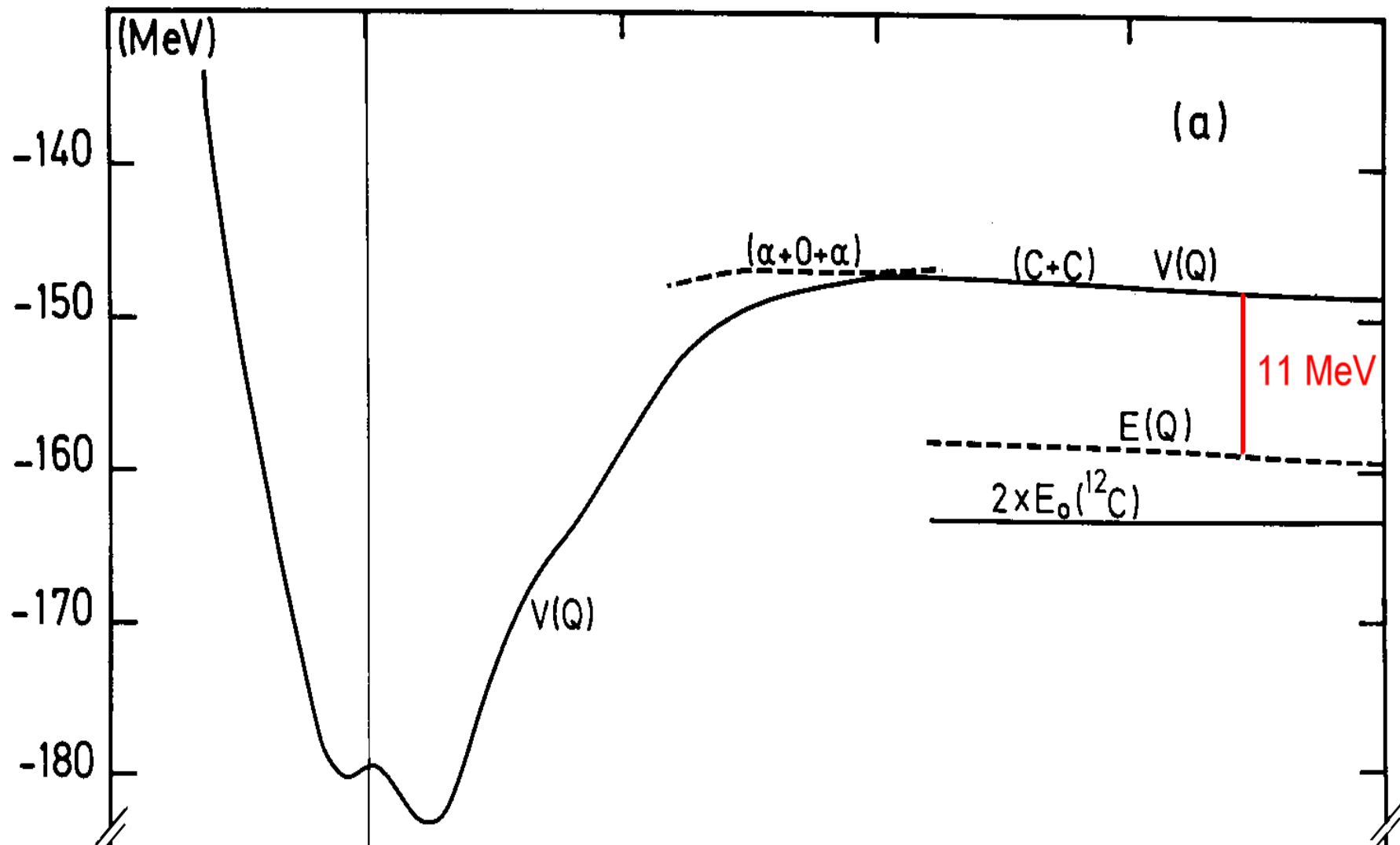
$$\hat{H}' = \hat{H}_1 + \hat{H}_2 + V_{coul} - \frac{\hat{P}^2}{2AM}$$

$$\hat{H}' \neq \left(\hat{H}_1 - \frac{\hat{P}_1^2}{2A_1M} \right) + \left(\hat{H}_2 - \frac{\hat{P}_2^2}{2A_2M} \right) + V_{coul}$$

- Energy difference:

$$\left\langle \frac{\hat{P}^2}{2A M} - \frac{\hat{P}_1^2}{2A_1M} - \frac{\hat{P}_2^2}{2A_2M} \right\rangle = \left\langle \frac{\hat{P}_R^2}{2\mu M} \right\rangle$$

~11 MeV in $^{12}\text{C} + ^{12}\text{C}$



$Q = \langle Q_{20} \rangle$ mass quadrupole deformation

- Potential for dynamics

$$V(Q) = E(Q) - \varepsilon_0(Q)$$

$$\varepsilon_0(Q) = \text{"zero-point energy correction"}$$

- At large distance R

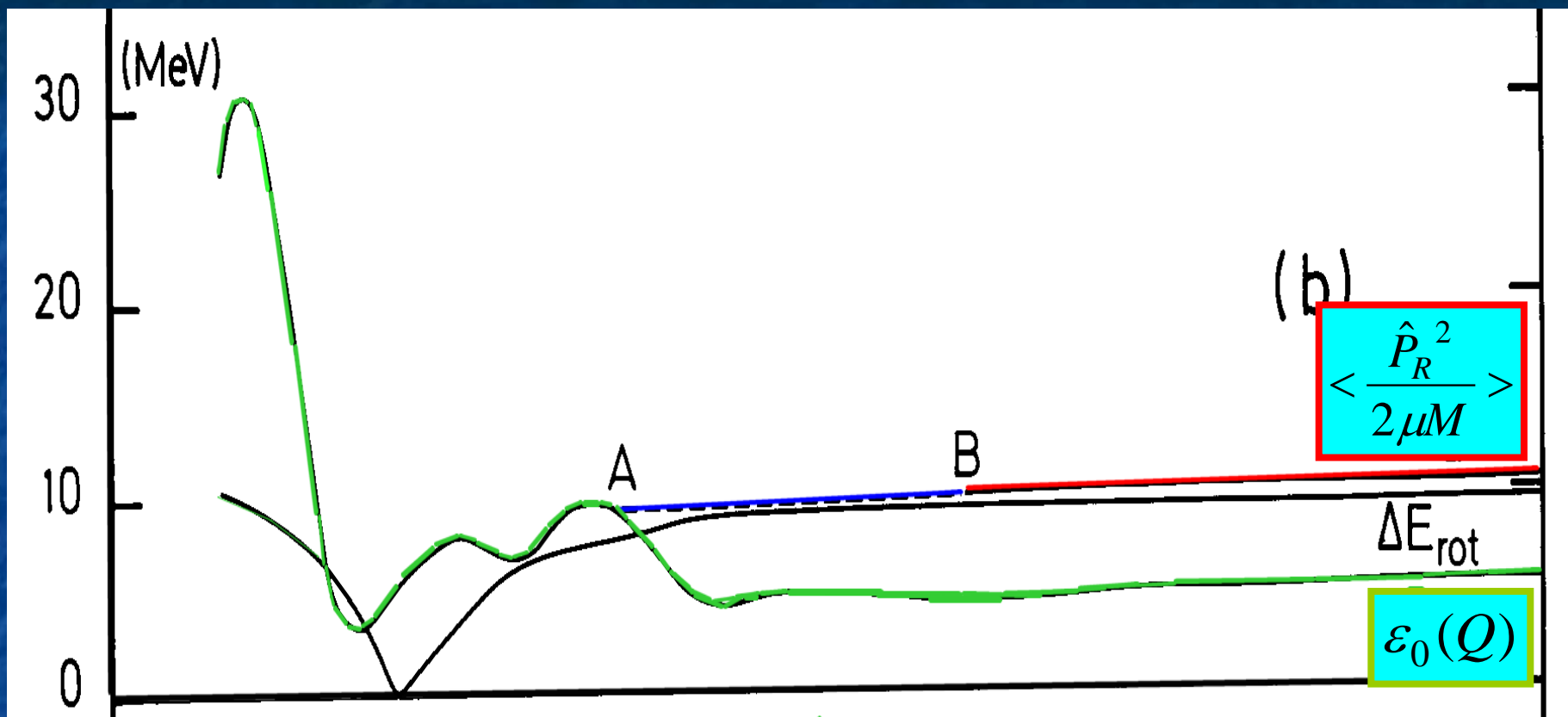
$$Q \rightarrow 2\mu R^2 + Q^{(1)} + Q^{(2)}$$

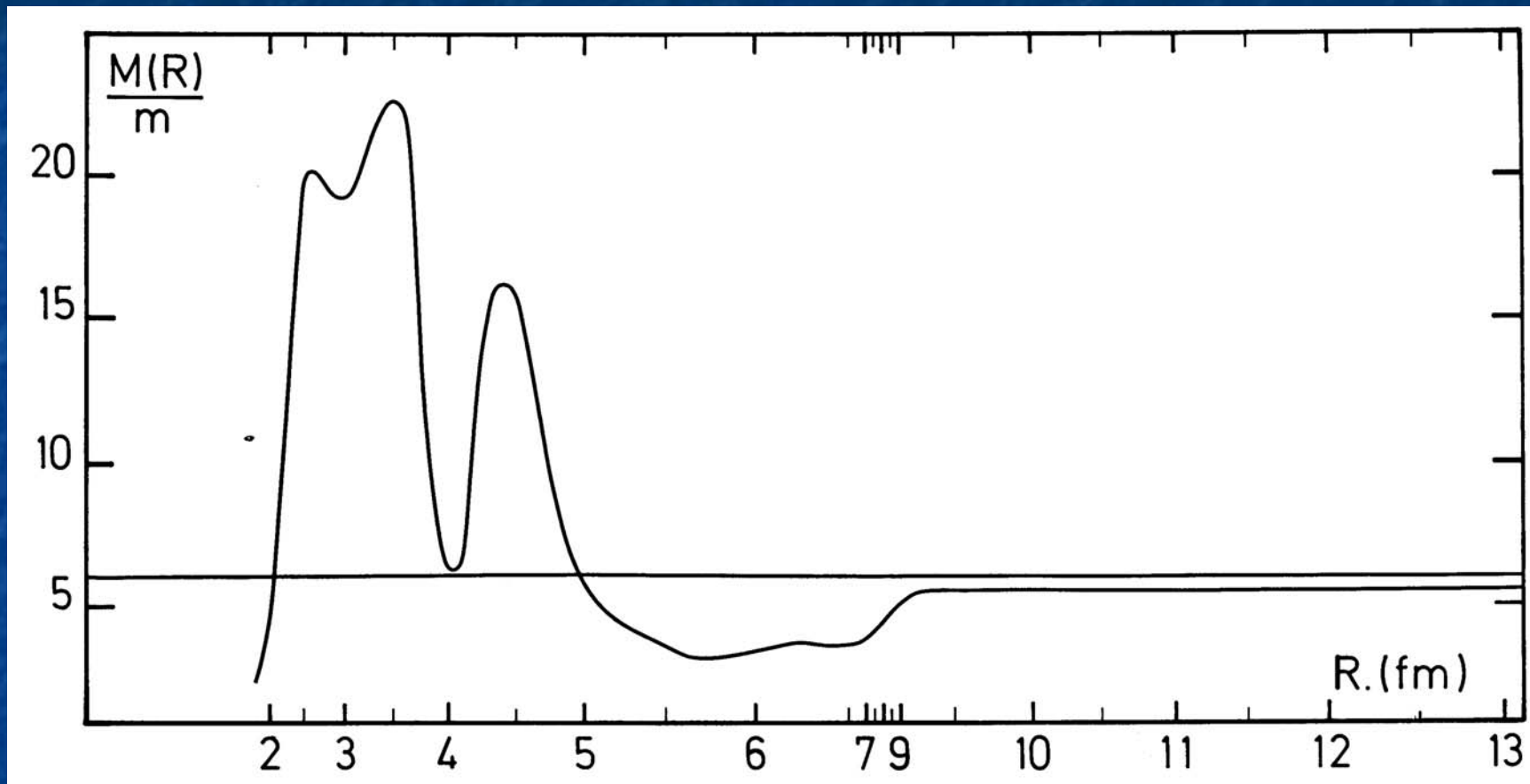
- Hence :

$$\varepsilon_0(Q) \approx \left\langle \frac{(i\partial / \partial Q)^2}{2M(Q)} \right\rangle \rightarrow \left\langle \frac{\hat{P}_R^2}{2\mu M} \right\rangle$$

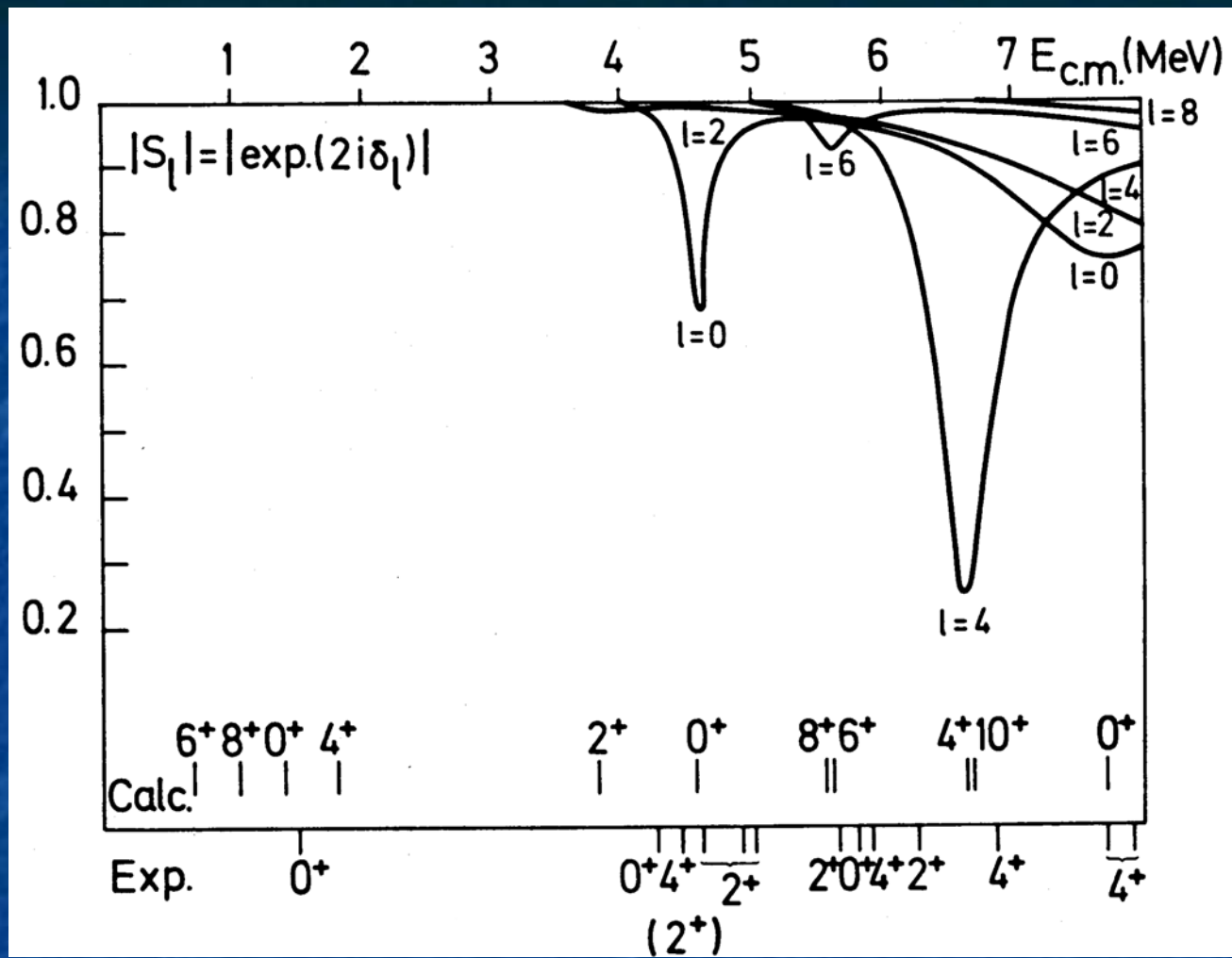
So removing everywhere the "zero-point energy correction" should correct for the spurious CM energy

Actually, this does not work very well





Inglis-Belyaev formula



Fission

270

Jülich 1979

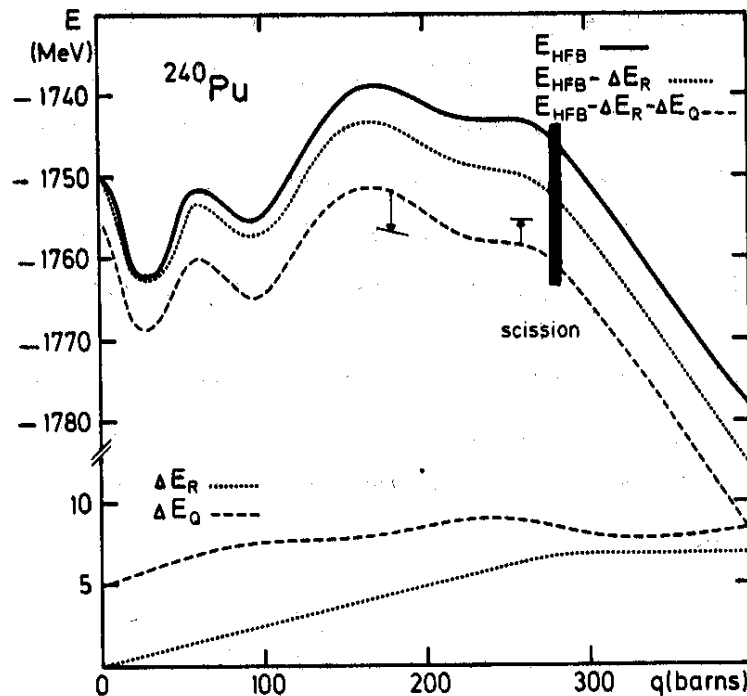


FIG.1. Courbes d'énergie potentielle et corrections effectuées. La courbe en trait plein (E_{HFB}) est le résultat du calcul Hartree-Fock-Bogolyubov avec contrainte sur le moment quadrupolaire de masse. Les deux autres courbes ont été obtenues en ôtant l'énergie cinétique du mouvement relatif des préfragments (ΔE_R) puis les énergies parasites de rotation-vibration (ΔE_Q) représentées au bas de la figure. Les deux flèches indiquent les corrections apportées par un calcul préliminaire permettant l'asymétrie de masse. La bande foncée verticale indique la position du point de scission.

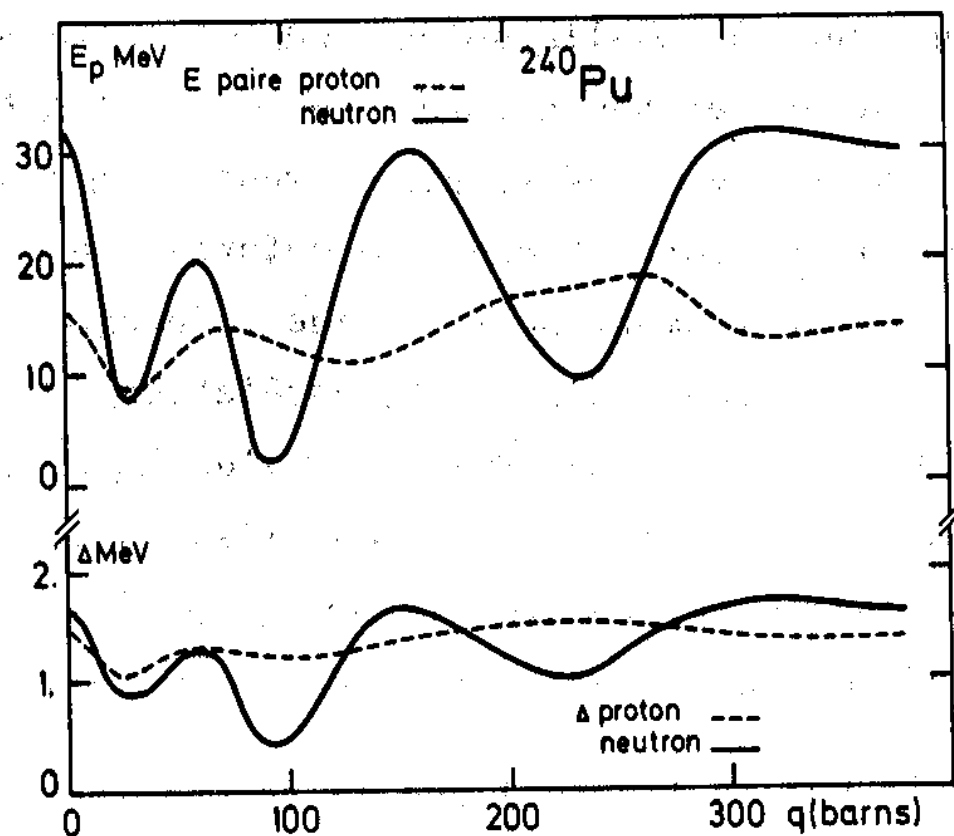
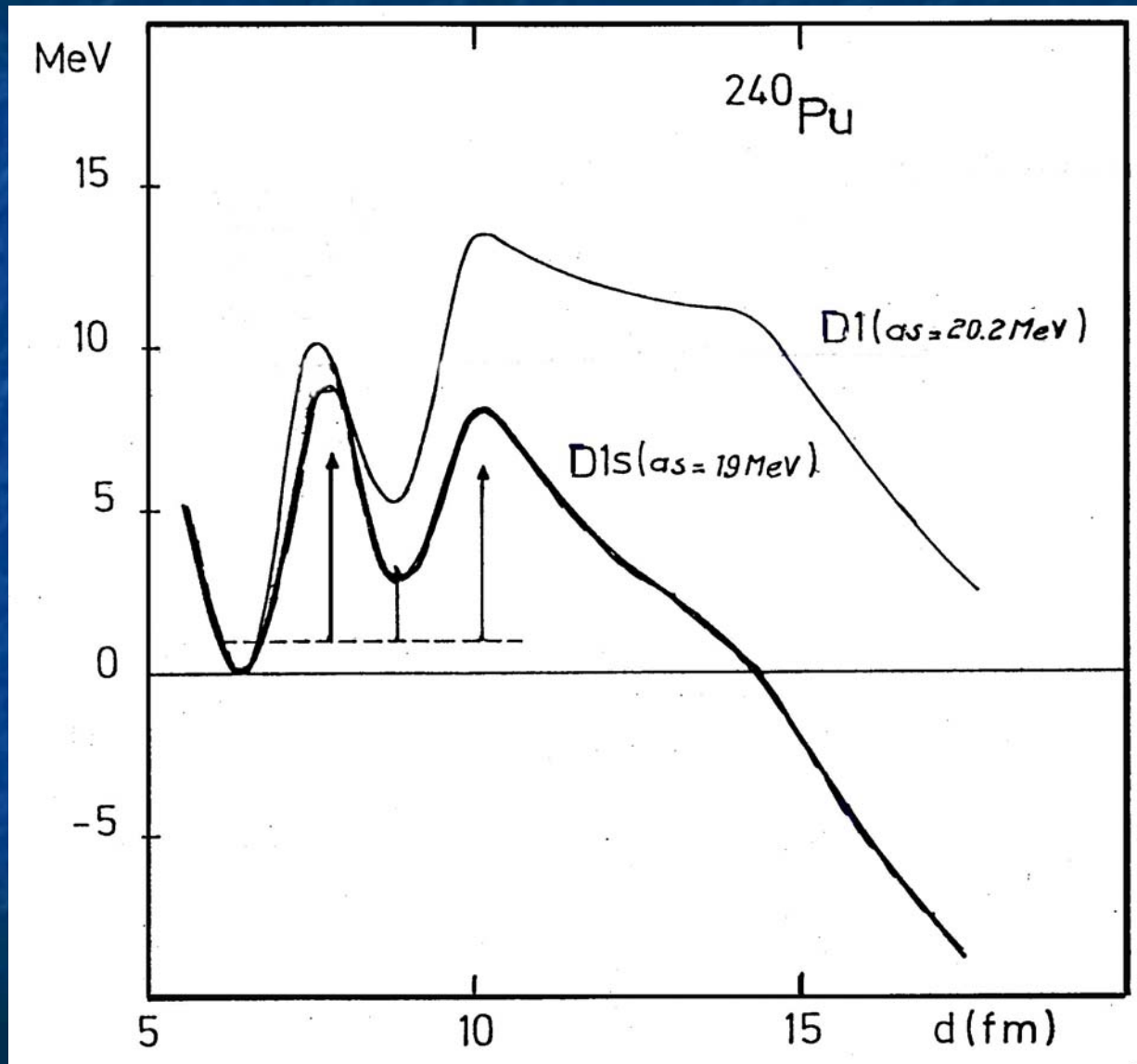
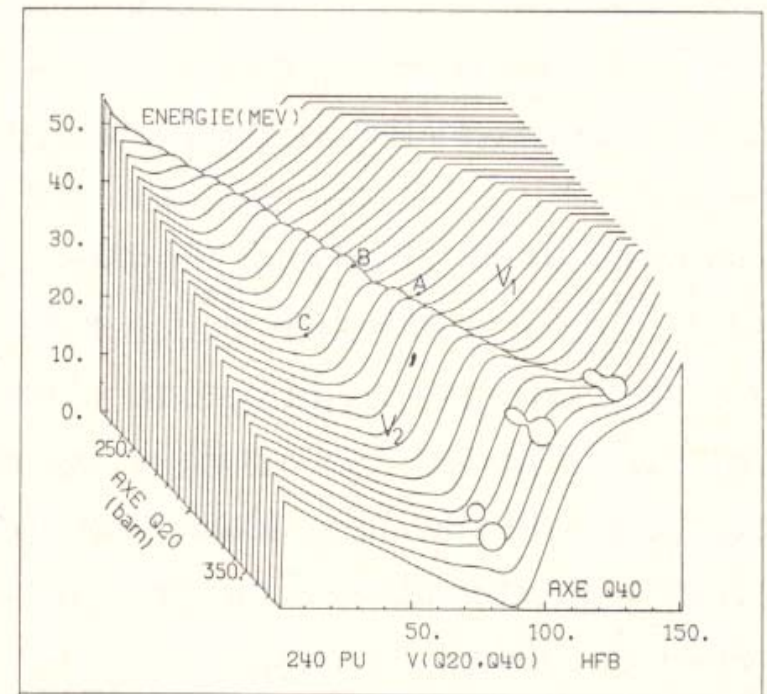
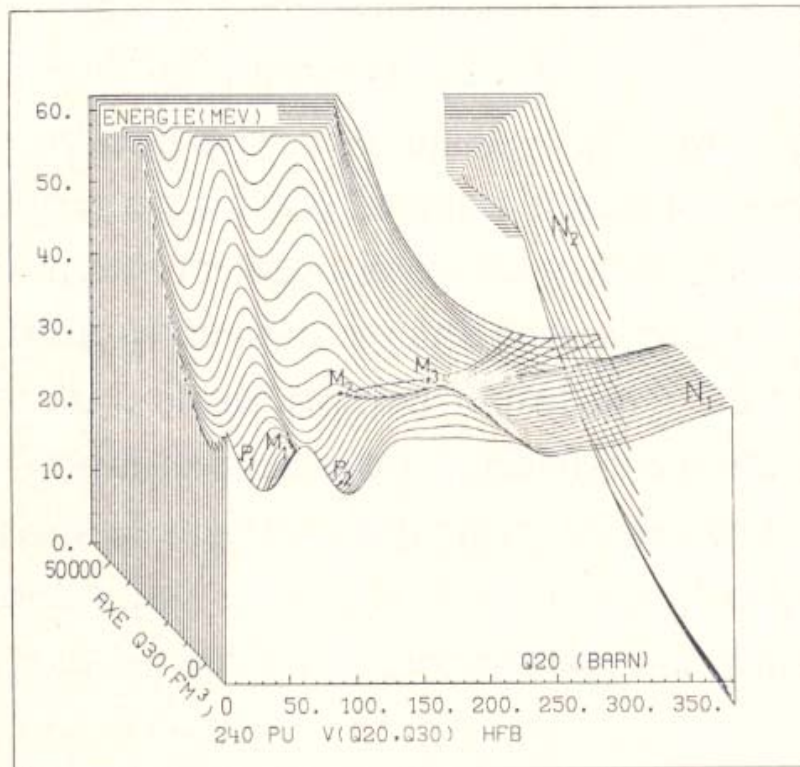
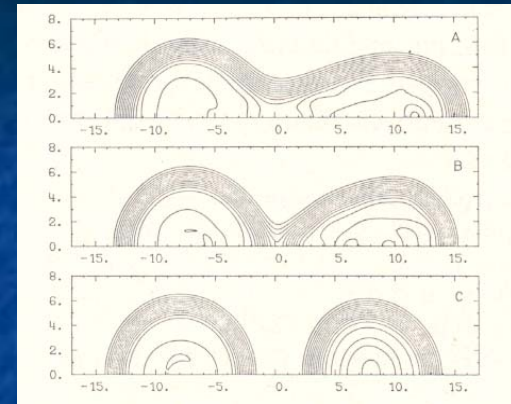


FIG.3. Variations en fonction de la déformation de l'énergie d'appariement E_p et de la plus petite énergie de quasiparticule Δ pour les protons (tirets) et les neutrons (trait plein).

Fission barrier of ^{240}Pu and D1S



Scission



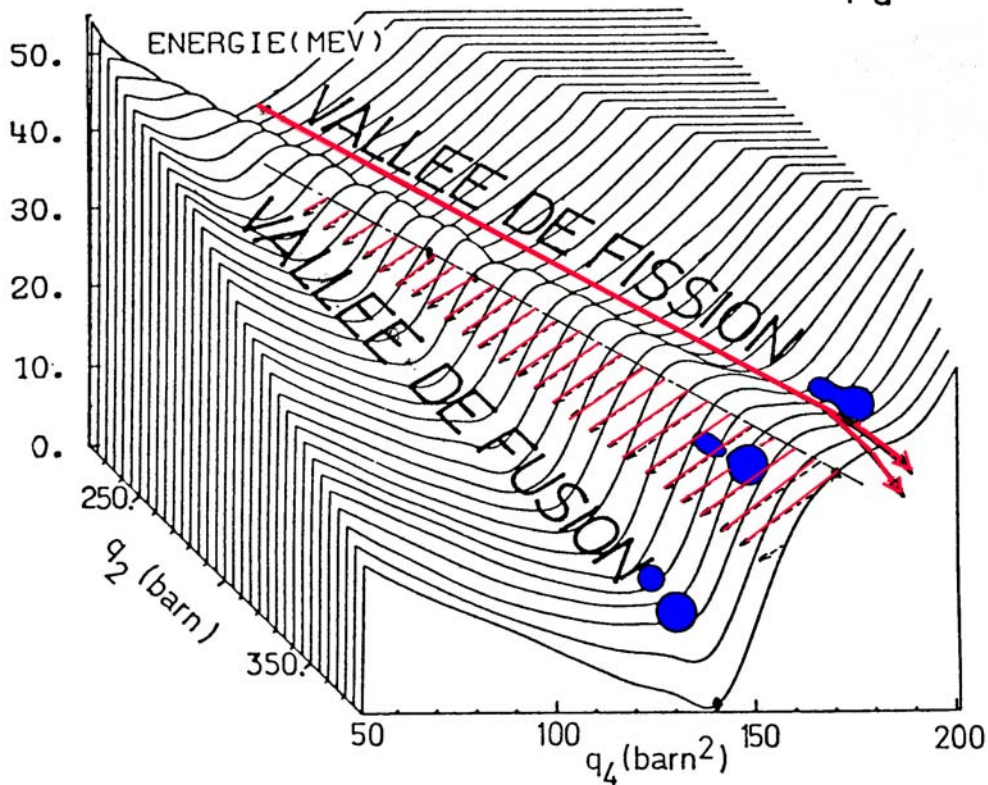
PHYSIQUE NUCLÉAIRE. — *Description microscopique de la fission nucléaire*. Note (*) de **Jean-François Berger**, **Michel Girod** et **Daniel Gogny**, présentée par Robert Dautray.

Partant d'une description complètement microscopique du noyau, nous tentons d'interpréter la fission du noyau ^{240}Pu en termes de coordonnées collectives considérées comme variables dynamiques. Nous insistons en particulier sur le mécanisme de la scission.

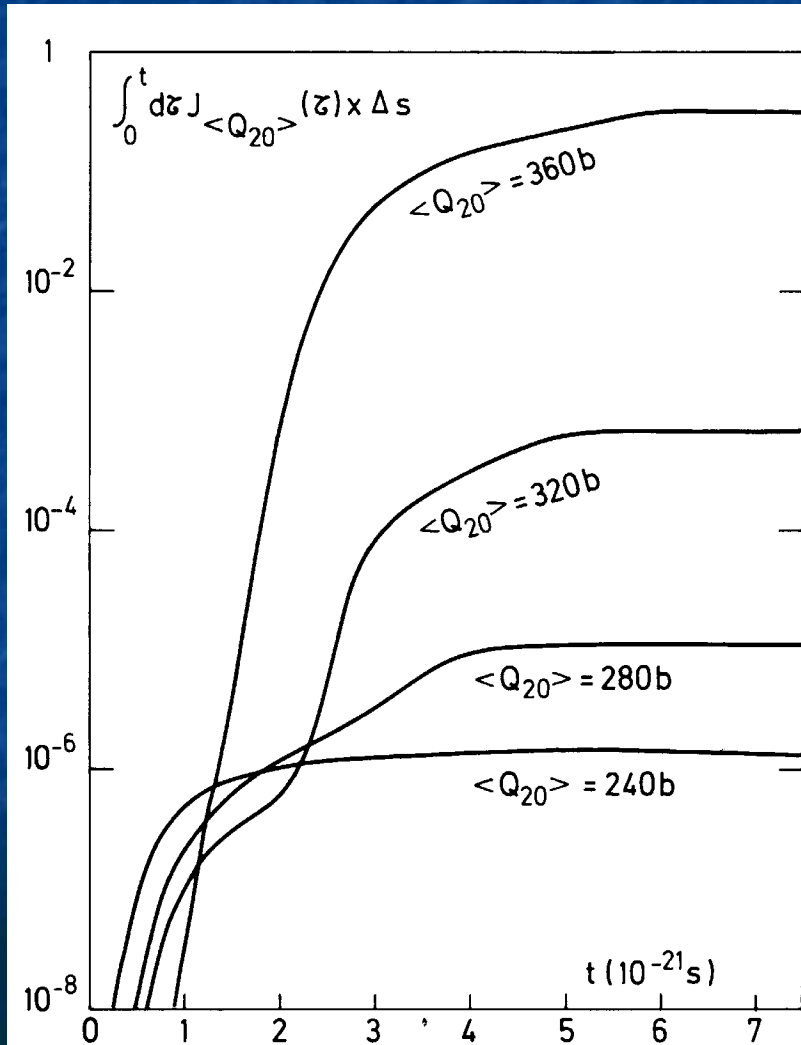
Starting from a completely microscopic description of the nucleus, we try to extract the characteristic features of the collective dynamics of the fission phenomenon in the case of the ^{240}Pu nucleus. In particular, we give an interpretation for the mechanism of the scission process.

La fission d'un noyau résulte d'un processus complexe qui fait intervenir deux types de mouvements. L'un est un mouvement cohérent de l'ensemble des nucléons qui conduit le noyau à s'étirer puis à se briser en deux fragments. L'autre est le mouvement interne des nucléons dans le champ nucléaire du système en cours de déformation. Naturellement ces deux types de mouvement ne sont pas indépendants. En particulier la structure interne du système — qui évolue au cours de la fission — conditionne étroitement la dynamique du mouvement cohérent. Dans le cas de la fission binaire spontanée ou induite à basse énergie, le mouvement cohérent du système peut être décrit à l'aide d'un petit nombre de paramètres, dits collectifs (q_1, q_2, \dots) qui caractérisent la forme du noyau. Les plus importants de ces paramètres sont ceux qui mesurent l'élongation totale du système, son asymétrie droite-gauche et son asymétrie axiale. Par ailleurs le temps caractéristique associé au mouvement cohérent ($\sim 10^{-21}$ s) étant nettement plus grand que celui associé au mouvement interne des nucléons ($\sim 10^{-22}$ s), on peut considérer que le mouvement interne est rapide par rapport au mouvement cohérent.

^{240}Pu



Scission dynamics



Cold fission

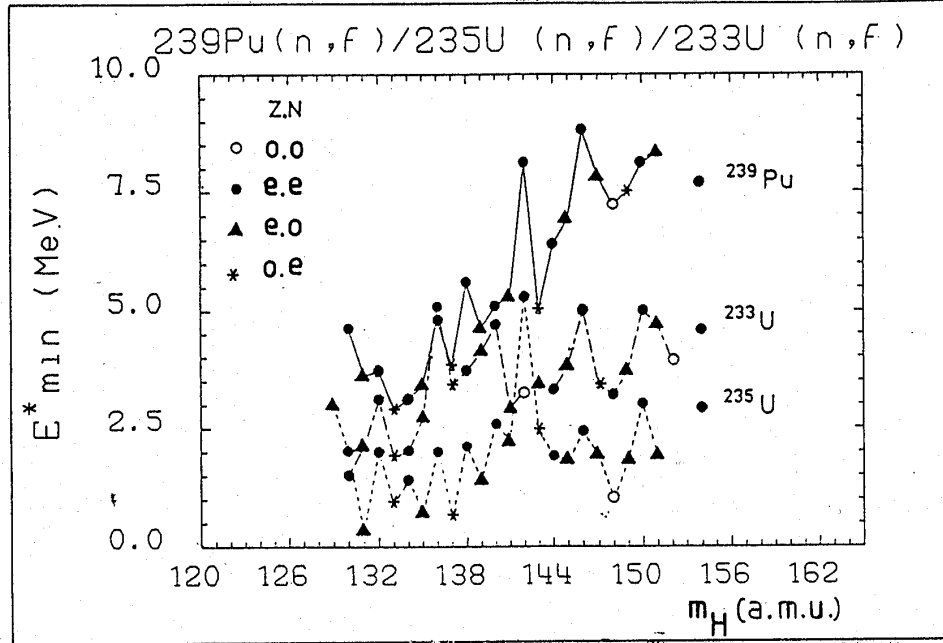


Fig.4. ^{233}U , ^{235}U and ^{239}Pu thermal neutron-induced fission. Minimum total fragment excitation energy E^*_{min} dependence with heavy mass.

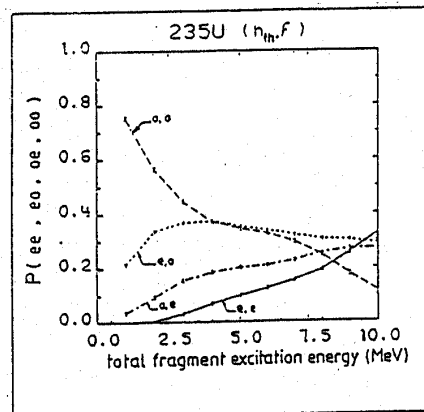
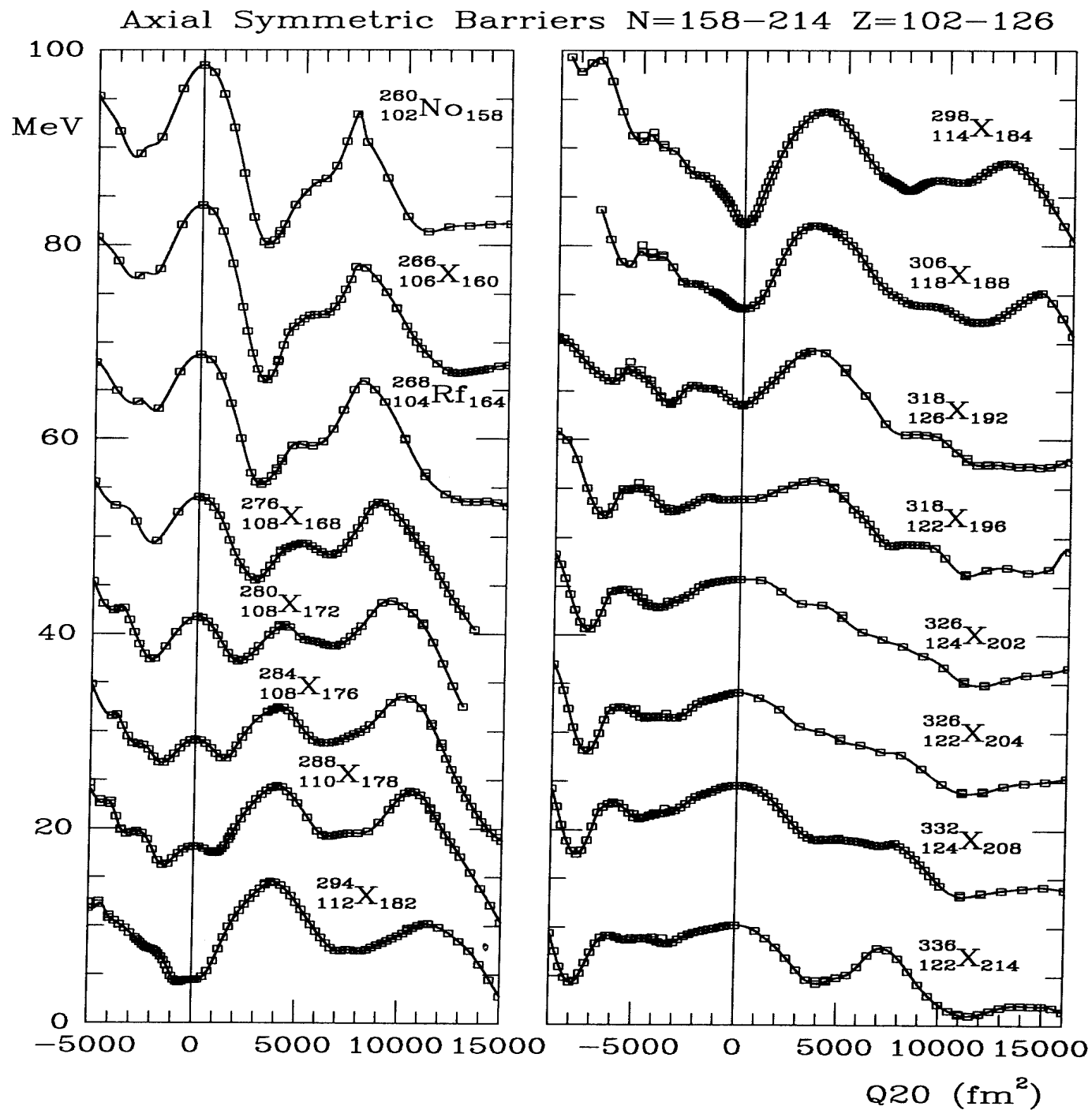
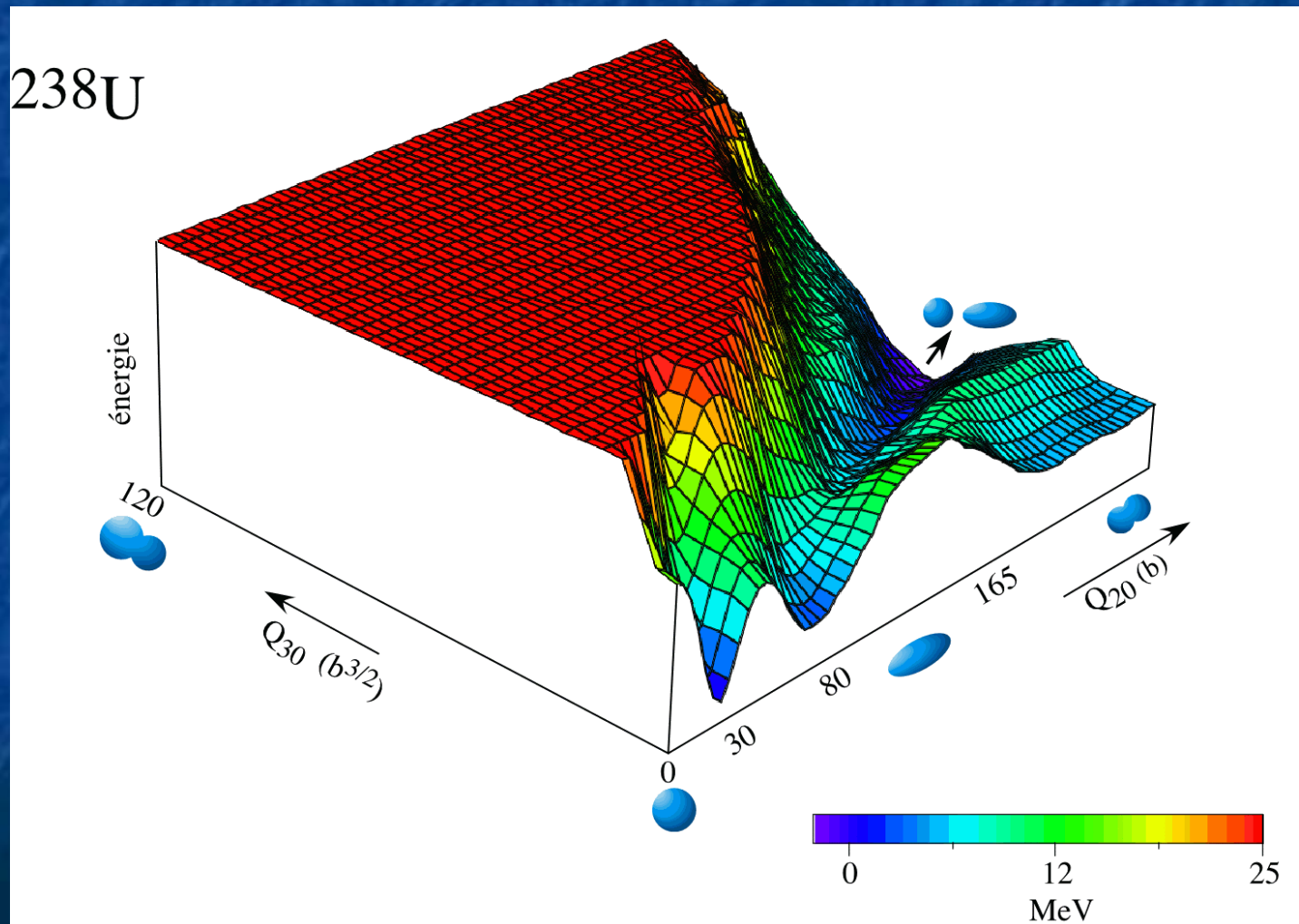


Fig.5. ^{235}U (n_{th}, f) fragment yield versus total excitation energy $E^*_{i,j}$ for odd-odd, odd-even, even-odd and even-even charge-neutron fragmentations. $E^*_{i,j} = Q_{i,j} - TKE_{i,j}$ for the charge and mass fragmentation i,j .

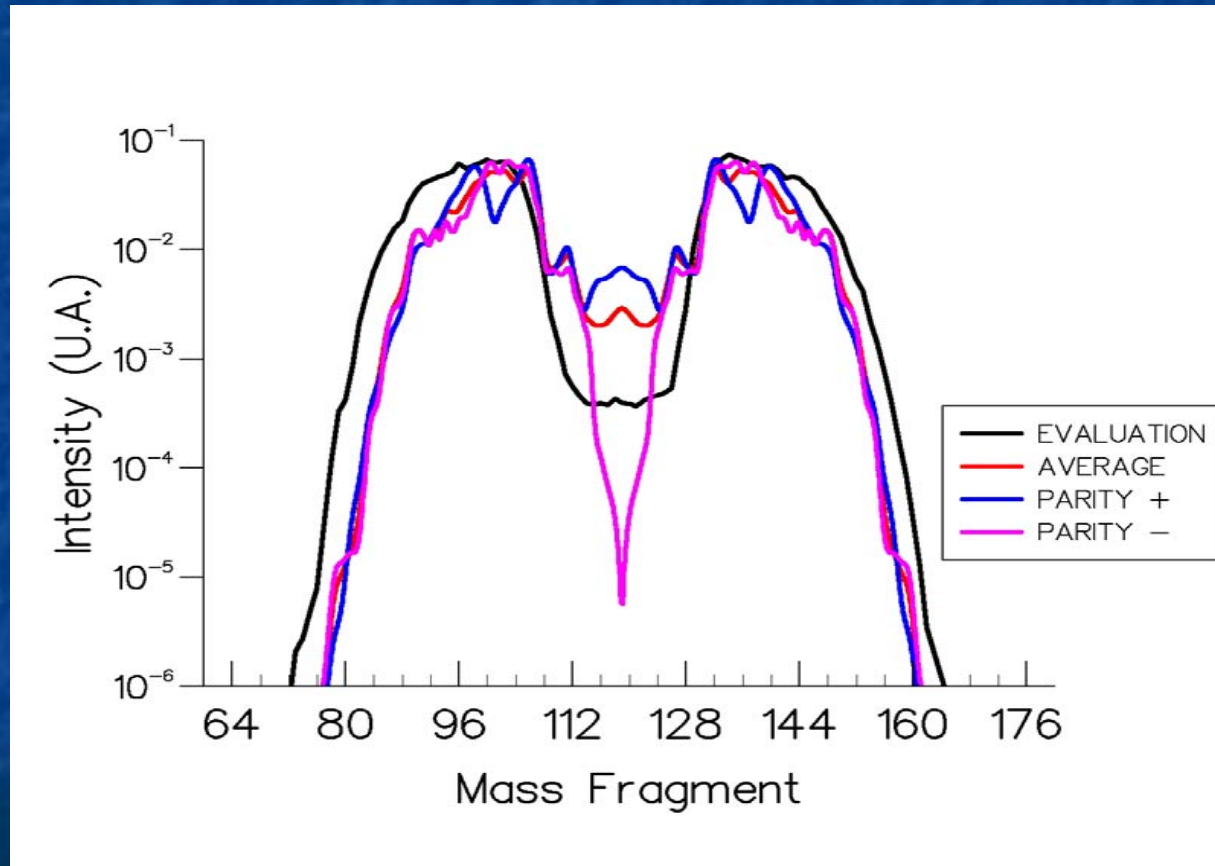
SHE



Fission 21st century

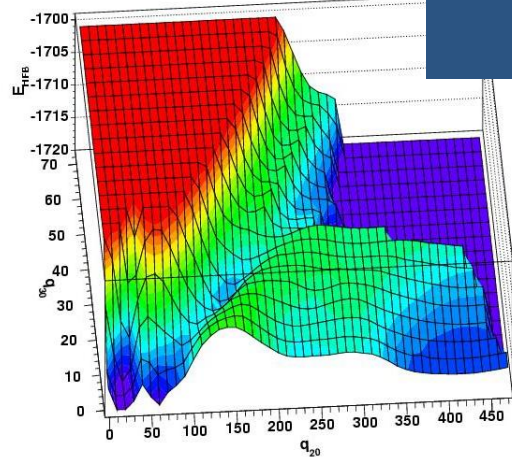


H.Goutte, JFB, P.Casoli and D. Gogny, Phys. Rev. C71 (2005) 024316

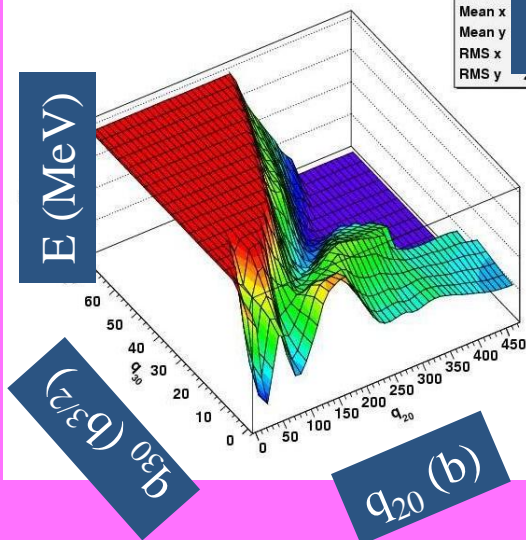


^{256}Fm

^{226}Th

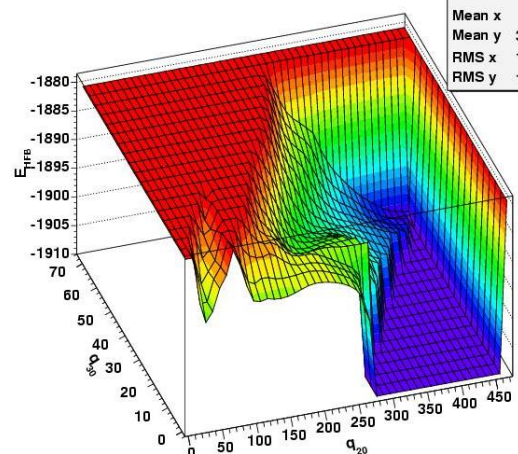


^{238}U



^{238}U

^{256}Fm



Outlook (Daniel Gogny's expertise needed)

- Theory and Evaluation : how to relate multi-dimensional PES with the one-D barriers which are so successful in data evaluation ?
- Photofission
- Nucleus-nucleus reactions at low energy : SHE production / structure

