Intermediate amplitude collective motion in ^{52}Ti with TDHFB

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Introduction

Time-dependent mean-field theories

Small amplitude → RPA, normal modes

Large amplitude
→ simulation of nuclear fusion and/or fission

The mean-field theory of nuclear structure and dynamics

J. W. Negele

Reviews of Modern Physics, Vol. 54, No. 4, October 1982

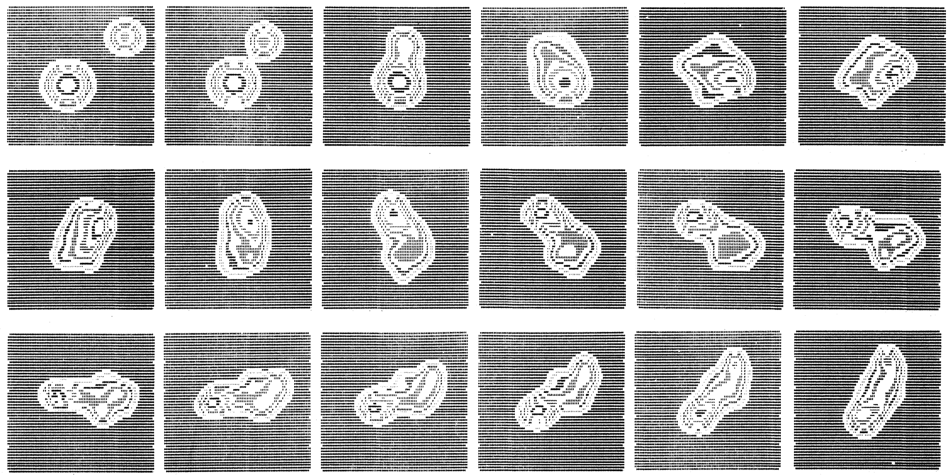


FIG. 39. Contour plots for the same reaction as in Fig. 38 with an initial angular momentum of $l = 60\hbar$.

energy transfer :

relative motion

→ internal collective/nucleonic motions

one-body dissipation

(2 body collision neglected)

its mechanism ???

← candidate : chaotic motion in TDHF (?)

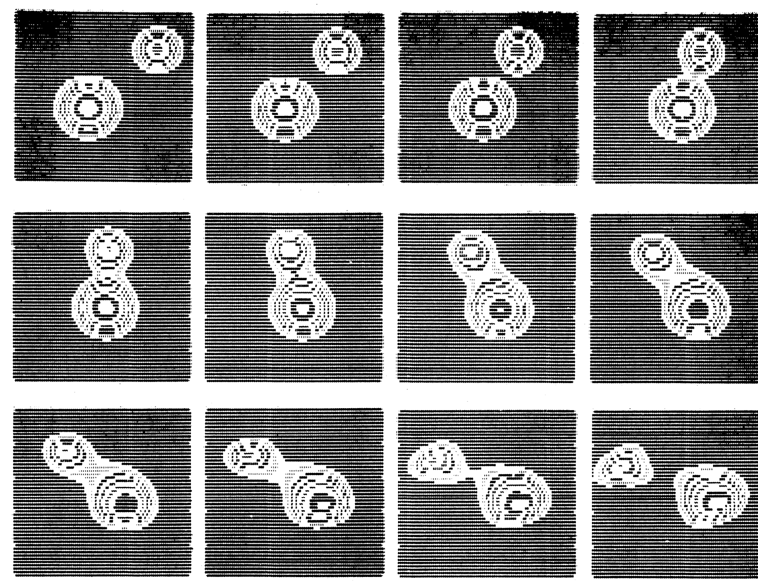


FIG. 40. Contour plots for the same reaction as in Fig. 38 with an initial angular momentum of $l = 80\hbar$.

Progress of Theoretical Physics, Vol. 95, No. 5, May 1996

A Numerical Study on the Structure Change of Collective Motions

Yukio HASHIMOTO, Kazuo IWASAWA,* Fumihiko SAKATA* and Akio NARUI

Skyrme SIII

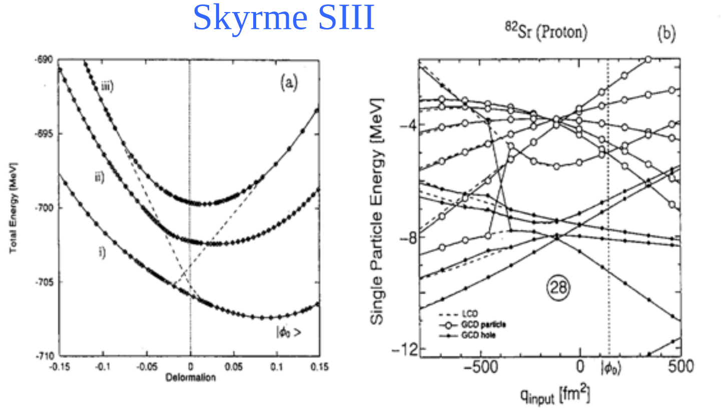


Fig. 1. (a) Continuous CHF lines. The lowest line i) passes through the ground state $|\phi_0\rangle$. The dense calculated points near $q=0.02$ and $q=-0.05$ indicate an abrupt character change occurring in line i). To illustrate "diabatic line" having no abrupt change, the dashed lines are drawn by hand. (b) The corresponding single-particle energy levels. Solid lines are results from the global configuration dictated (GCD) method, and dashed lines are from the local configuration dictated (LCD) method. The filled and open circles represent the occupied and unoccupied states, respectively. (Borrowed from Ref. 4)).

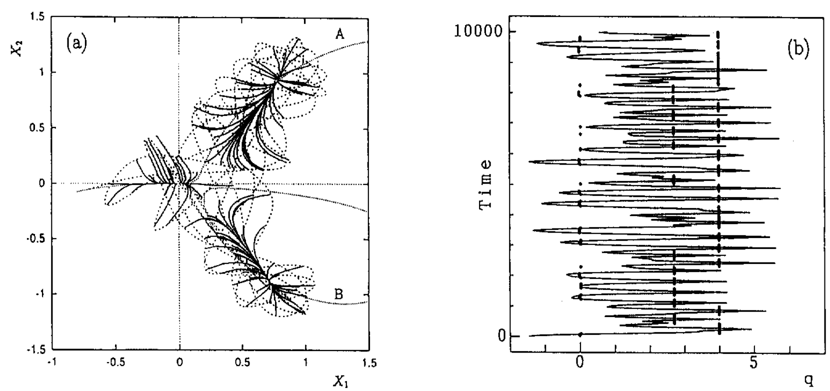
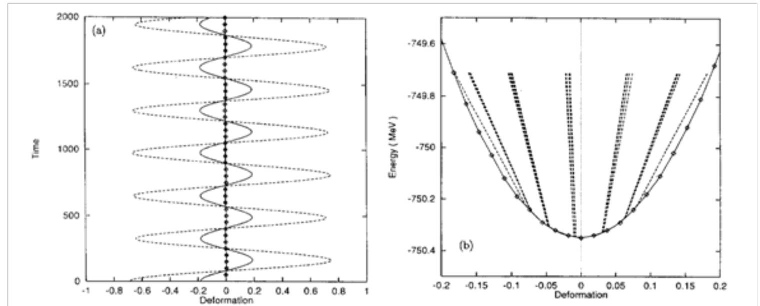


Fig. 8. (a) and (b) As in Fig. 6 but for the TDHF trajectory (dashed curve) in Fig. 5. The resulting points are ϕ_0, ϕ_1 and ϕ_2.

three-level model

BKN force



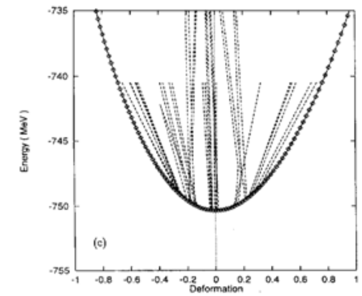
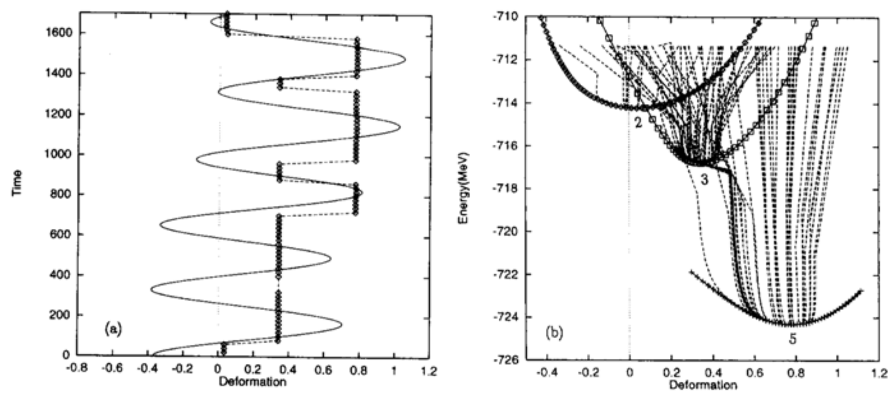


Fig. 10. (a) Density oscillations with small (full curve) and large (dashed curve) excitation energies. The resulting points obtained by the TR method are shown by open rhombuses (small amplitude) and pluses (larger amplitude). These are identical to the ground state. The iteration processes (dashed curves) of the TR method are shown for small-amplitude (b) and larger-amplitude (c) TDHF trajectories. The parabola represents the ground state branch in Fig. 9. The open rhombuses on the parabola in (b) and (c) denote the calculated points in the local configuration dictated (LCD) method.



From TDHF to TDHFB

☆ make clear the role of pairing correlation
in larger amplitude collective motion
(within mean-field framework)

☆ invent tools to understand the microscopic
(single-particle) dynamics

Equations of motion of matrices U & V

see Ring & Schuck

$$\boxed{i\hbar\frac{\partial}{\partial t}\begin{pmatrix} U(t) \\ V(t) \end{pmatrix} = \mathcal{H}\begin{pmatrix} U(t) \\ V(t) \end{pmatrix}}$$

$$\begin{aligned} i\hbar\frac{\partial}{\partial t}\mathcal{R} &= [\mathcal{H},\mathcal{R}], \\ \mathcal{H} &= \begin{bmatrix} h_1 & \Delta \\ \Delta^\dagger & -h_1^* \end{bmatrix}, \\ \mathcal{R} &= \begin{bmatrix} \rho & \kappa \\ \kappa^\dagger & 1-\rho^* \end{bmatrix}, \quad \mathcal{R} = \mathcal{R}^2 \end{aligned}$$

$$h \equiv t + \Gamma \qquad \Gamma_{ij} = \sum_{kl} \bar{v}_{ikjl}\rho_{lk} \qquad \Delta_{ij} = \frac{1}{2}\sum_{kl} \bar{v}_{ijkl}\kappa_{kl}$$

$$\rho_{ij} = \langle\Phi|c_j^\dagger c_i|\Phi\rangle = (V^*V^T)_{ij} \qquad \kappa_{ij} = \langle\Phi|c_j c_i|\Phi\rangle = (V^*U^T)_{ij}$$

Gogny-D1S

$$V_{12} = \sum_{i=1}^{2} \exp\left[-\frac{|\vec{r}_1 - \vec{r}_2|^2}{\mu_i^2}\right] \cdot (W_i + B_i\hat{P}_\sigma - H_i\hat{P}_\tau - M_i\hat{P}_\sigma\hat{P}_\tau) +$$

Gauss part

$$+t_3(1 + x_0\hat{P}_\sigma)\,\delta(\vec{r}_1 - \vec{r}_2)\left[\rho\left(\frac{\vec{r}_1 + \vec{r}_2}{2}\right)\right]^\gamma +$$

density dependen part

$$+iW_{\rm LS}(\vec{\sigma}_1 + \vec{\sigma}_2)\cdot \overleftarrow{\nabla}_{12} \times \delta(\vec{r}_1 - \vec{r}_2)\vec{\nabla}_{12} + V_{\rm Coul.}\,,$$

L-S part

Coulomb part is NOT included

μ_1 = 0.7 fm	μ_2 = 1.2 fm
W_1 = -1720.3 MeV	W_2 = 103.639 MeV
B_1 = 1300 MeV	B_2 = -163.483 MeV
H_1 = -1813.53 MeV	H_2 = 162.812 MeV
M_1 = 1397.60 MeV	M_2 = -223.934 MeV
t_3 = 1390.60 MeV fm$^{3(1+\gamma)}$	x_0 = 1
γ = 1/3	W_{LS} = 130 MeV fm^5

- basis function : three-dimensional harmonic oscillator wave functions
- space : $N_{shell} = n_x + n_y + n_z \le 5$

initial conditions:

- Q_{20} type impulse on ground state （impulse type）
- constrained state with quadrupole operator （constraint type）

initial U & V

$$V_k(t=0) \rightarrow \underline{\exp(i\epsilon Q_0)} V_k(t=0)$$

$$= \sum_{\nu} \frac{i^\nu \epsilon^\nu Q_0^\nu}{\nu!} V_k(t=0)$$

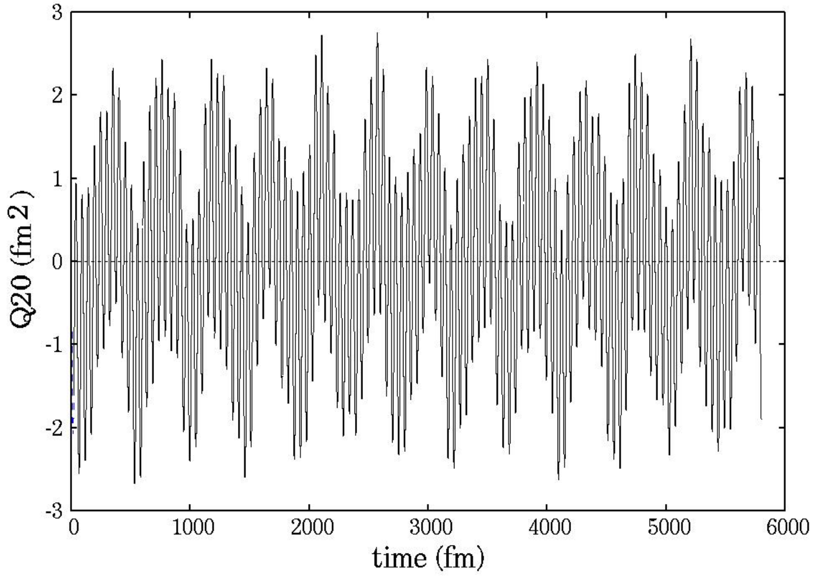
$$U_k(t=0) \rightarrow \underline{\exp(-i\epsilon Q_0^*)} U_k(t=0)$$

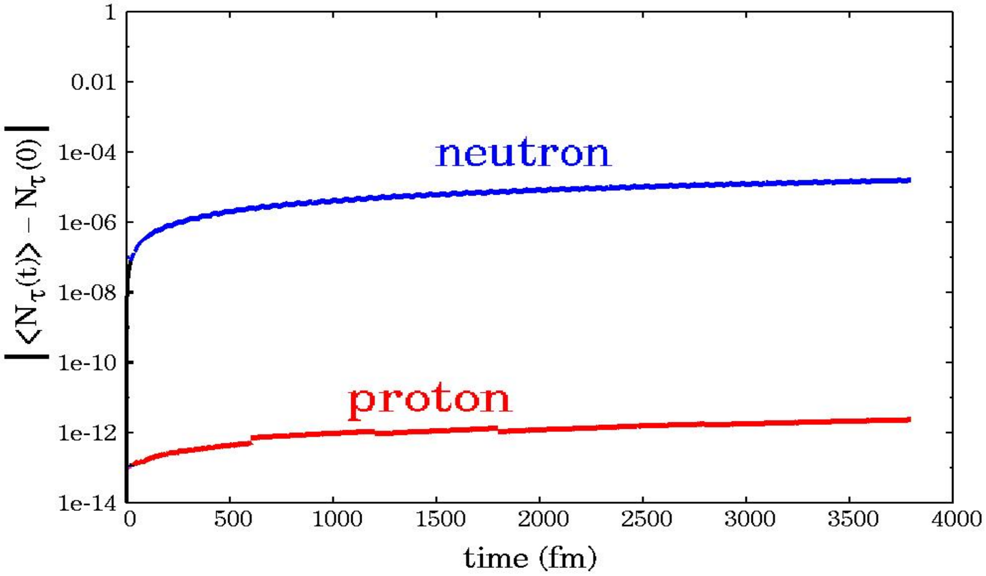
HFB ground state U, V

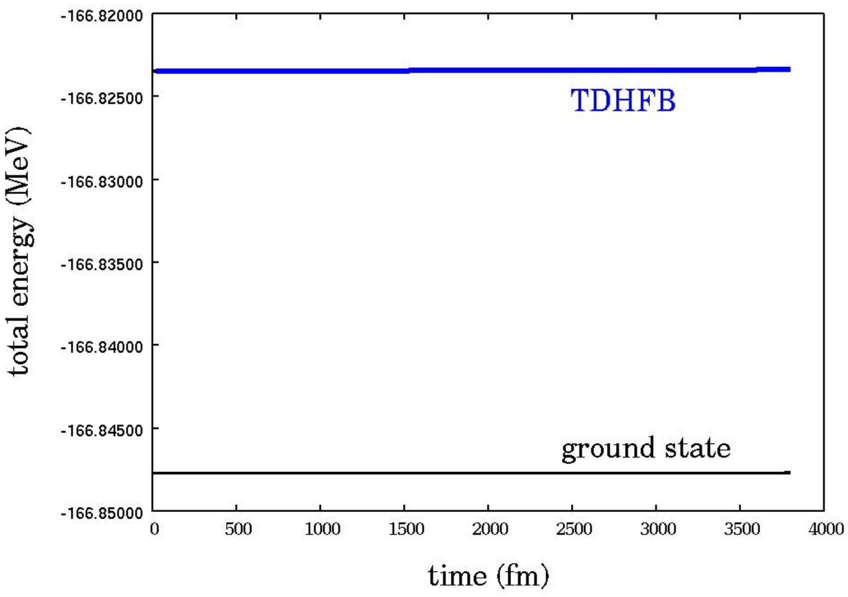
Q_0：matrix representation of multipole operator

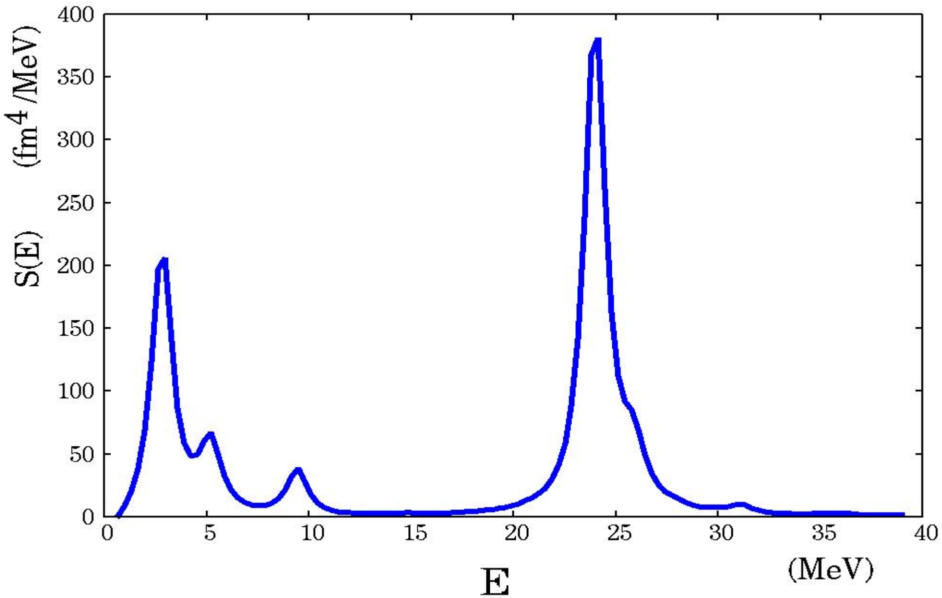
$$Q_{20} = 2z^2 - x^2 - y^2 \ [\mathrm{fm}^2]$$

Example-1: ^{20}O quadrupole oscillation



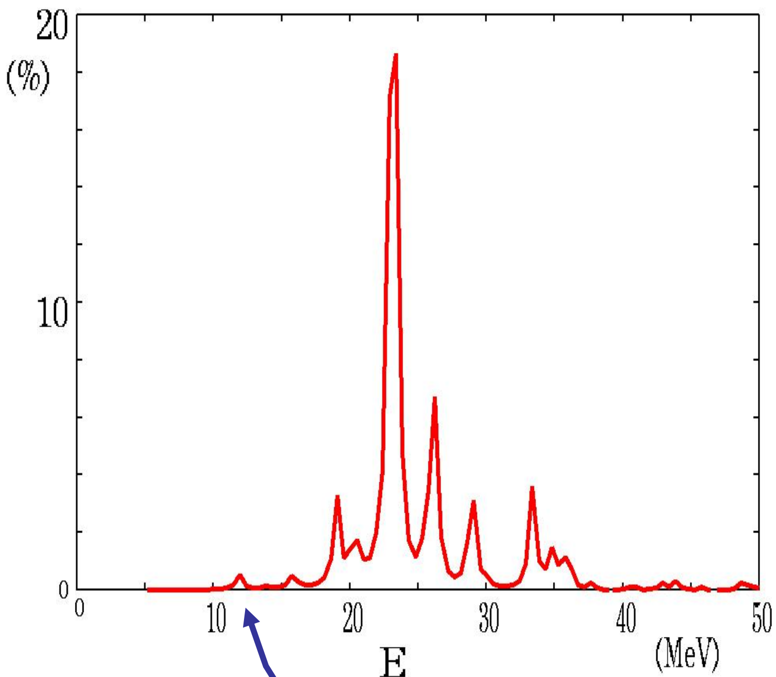


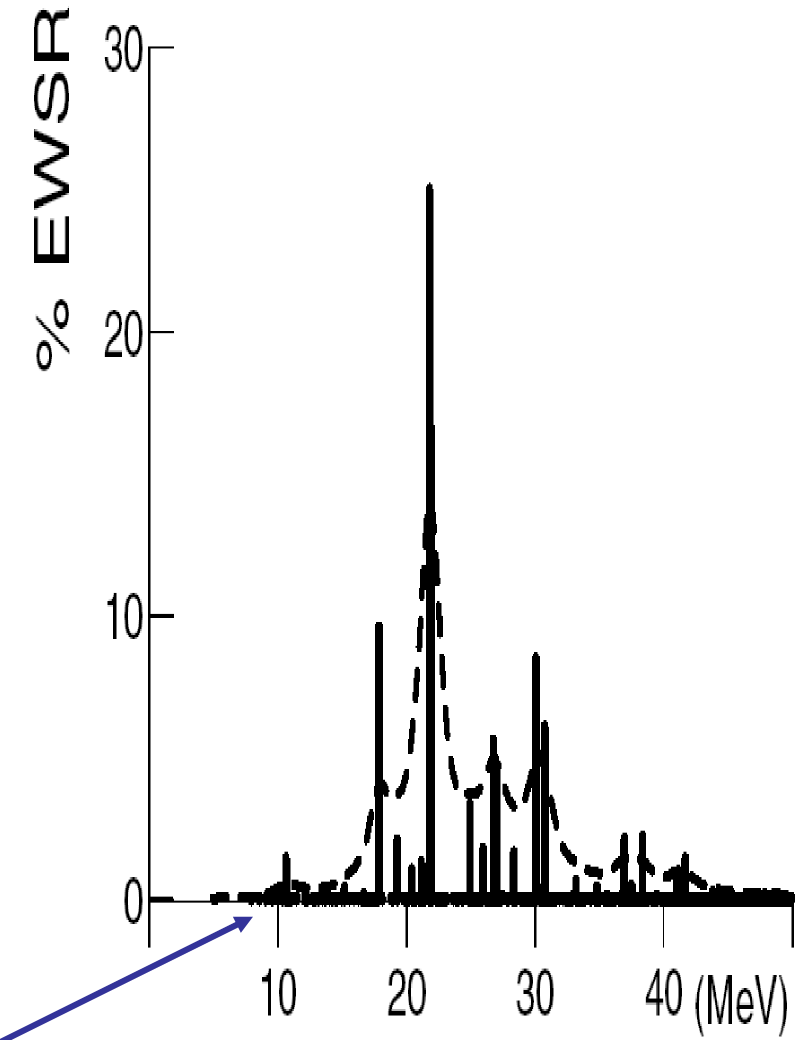




Example-2. Spherical case: ^{26}Ne IV dipole response

TDHFB (Nshll = 5)



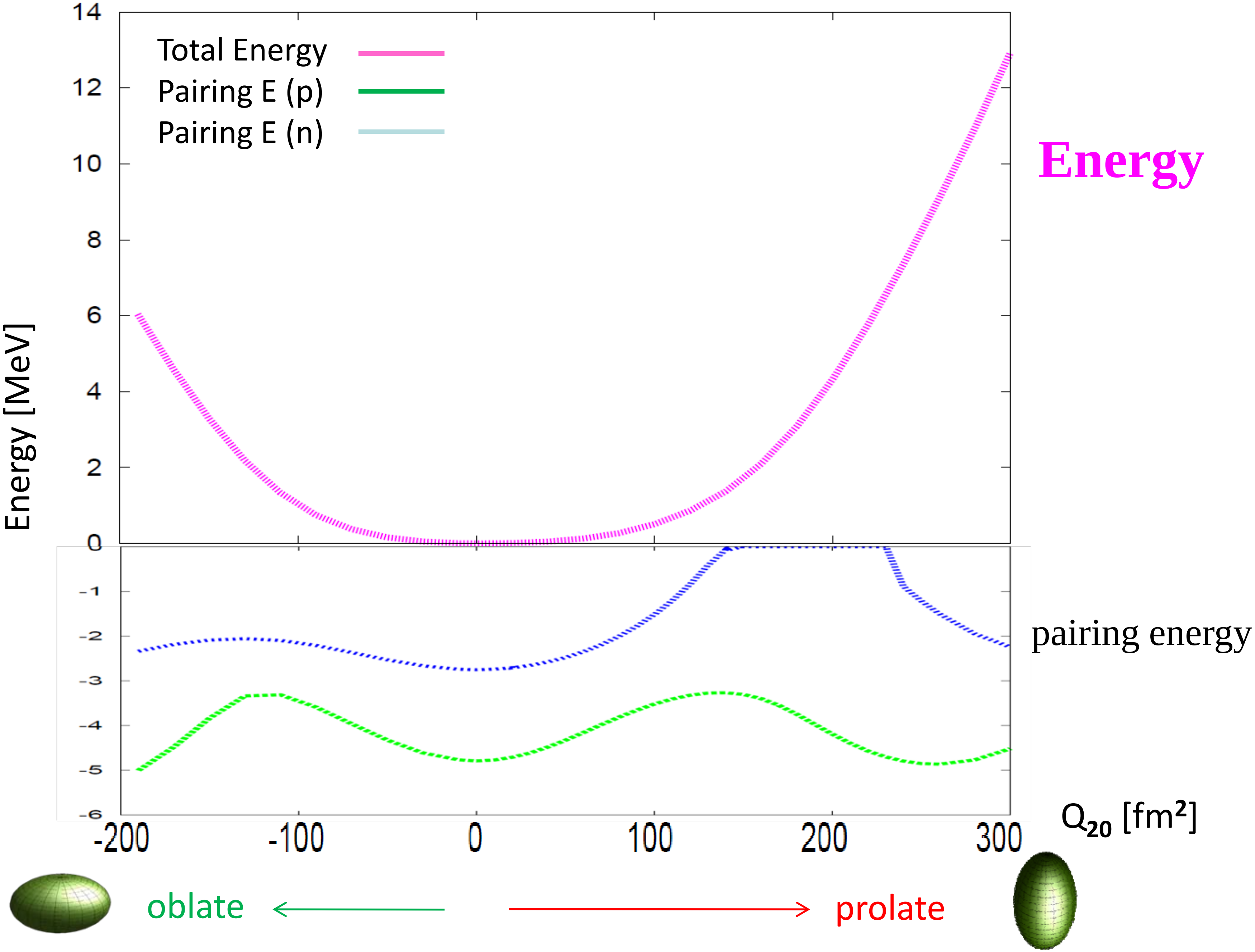


S. Peru, H. Goutte, J.F. Berger, Nucl. Phys. A788(2007), 44-49.

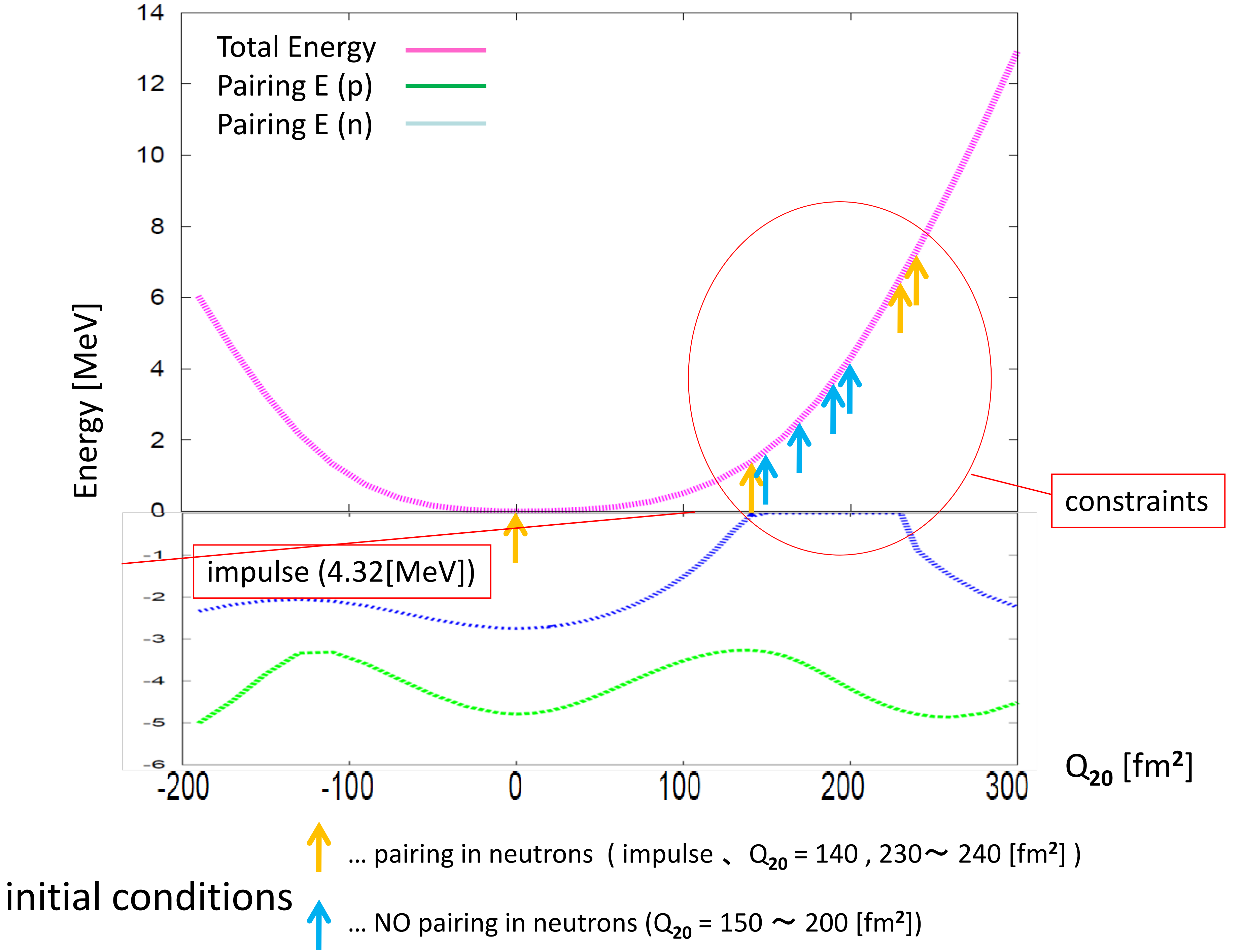
^{52}Ti results

☆ Larger ecitation energy

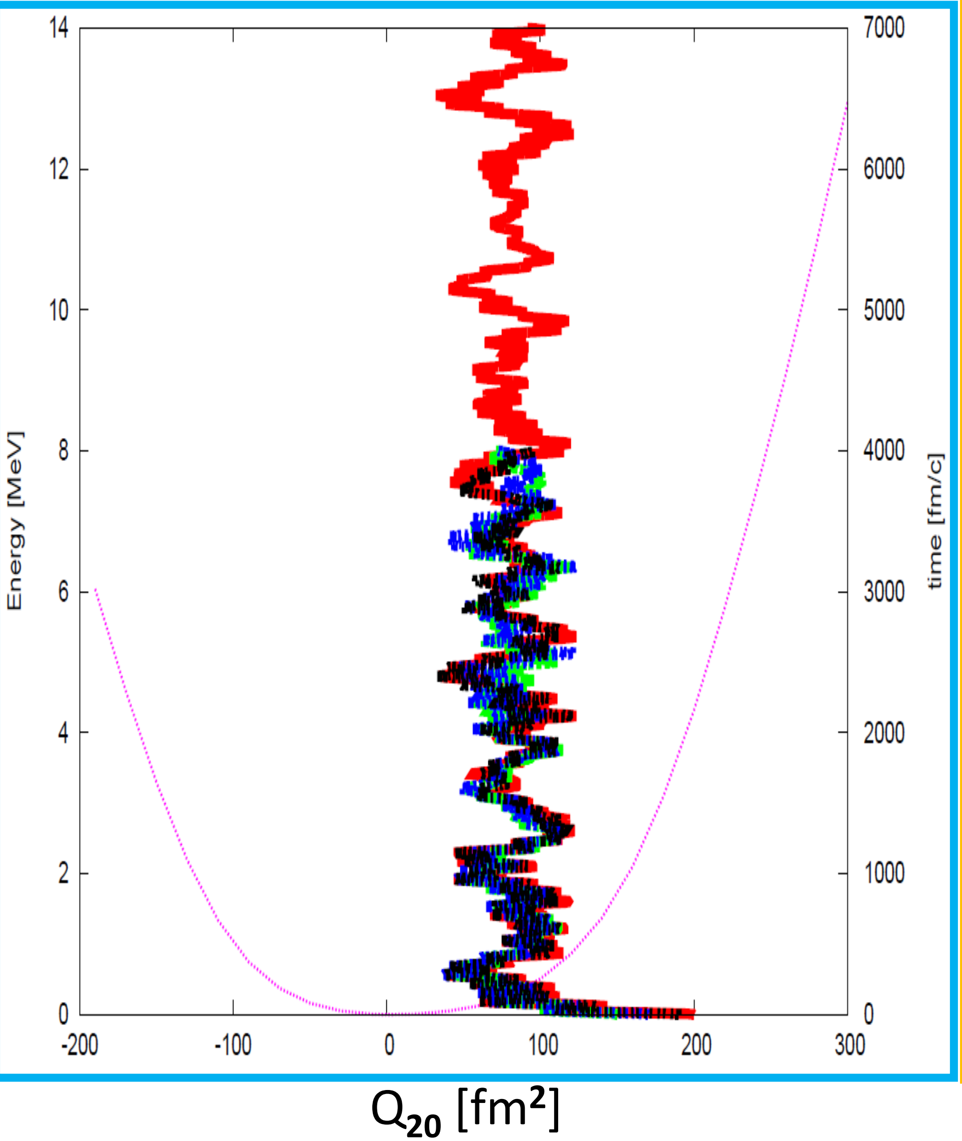
☆ Larger amplitude ← “intermediate amplitude”

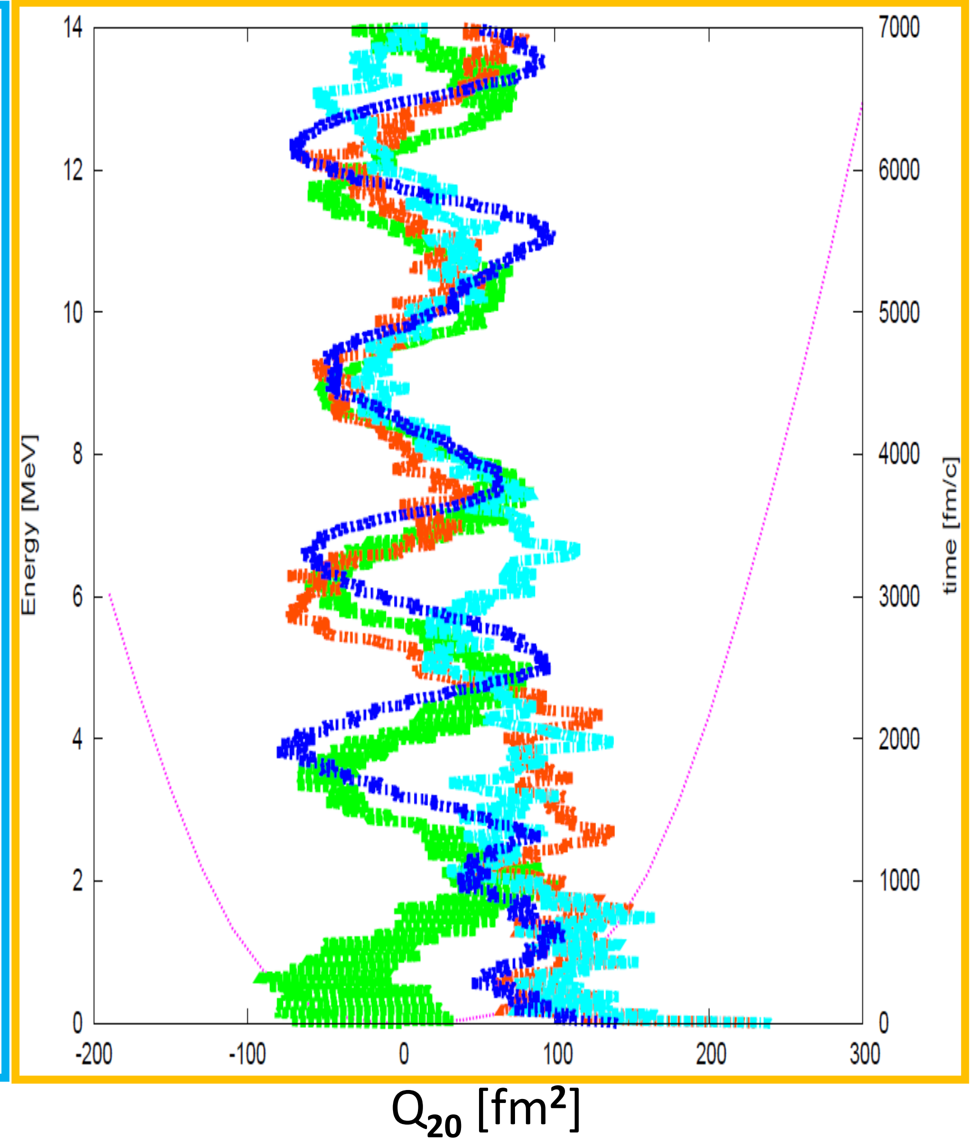


energy curve E vs $\langle Q_{20} \rangle$ (^{52}Ti (Z = 22, N = 30))



Total Energy
Pairing E (p)
Pairing E (n)
Energy [MeV]
14
12
10
8
6
4
2
0
-1
-2
-3
-4
-5
-6
-200
-100
0
100
200
300
Q20 [fm2]
constraints
impulse (4.32[MeV])
initial conditions
… pairing in neutrons（impulse 、 Q20 = 140 , 230〜 240 [fm2])
… NO pairing in neutrons (Q20 = 150 〜 200 [fm2])



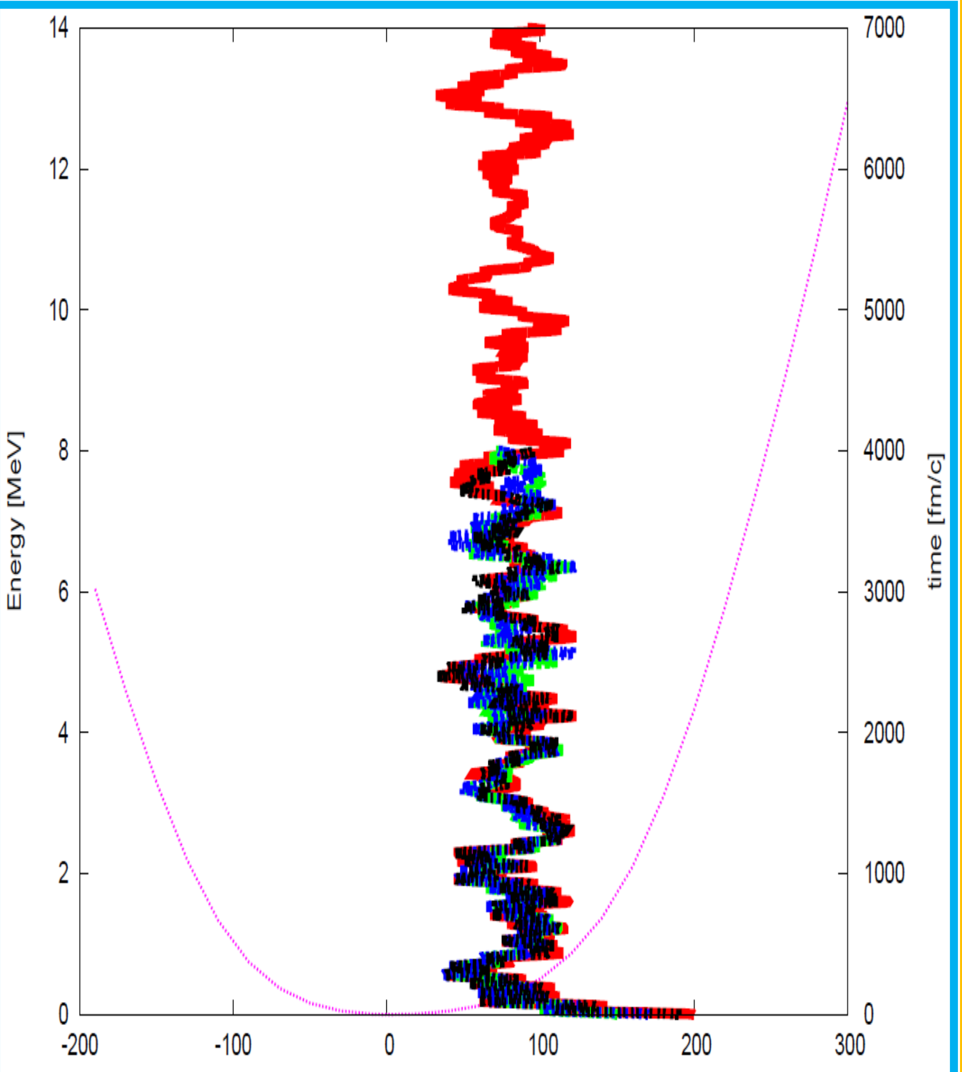


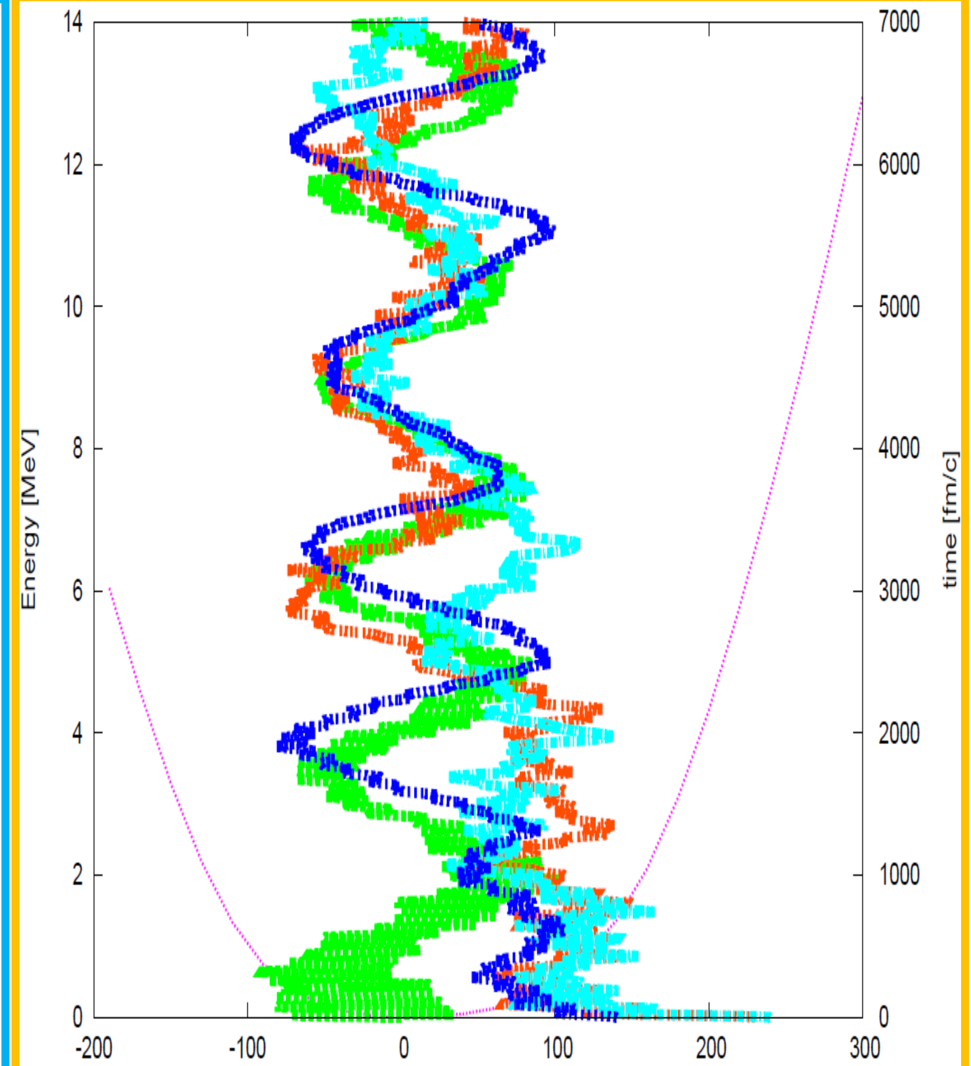
… no pairing in neutrons

oscillation around Q_{20} = 85 [fm^2]

… pairing in neutrons

oscillations around Q_{20} = 0 [fm^2]

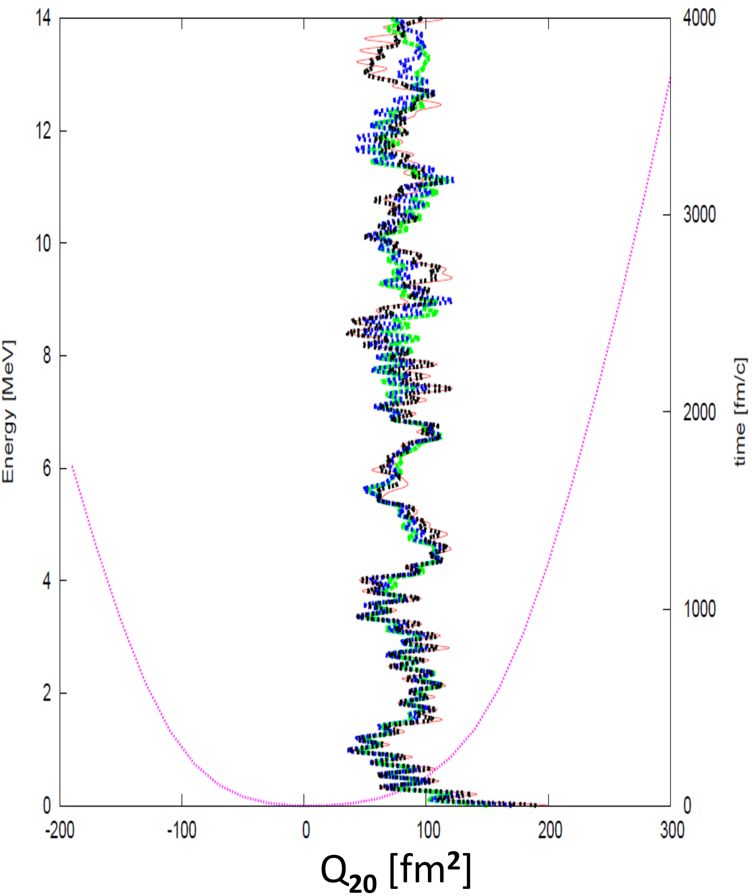




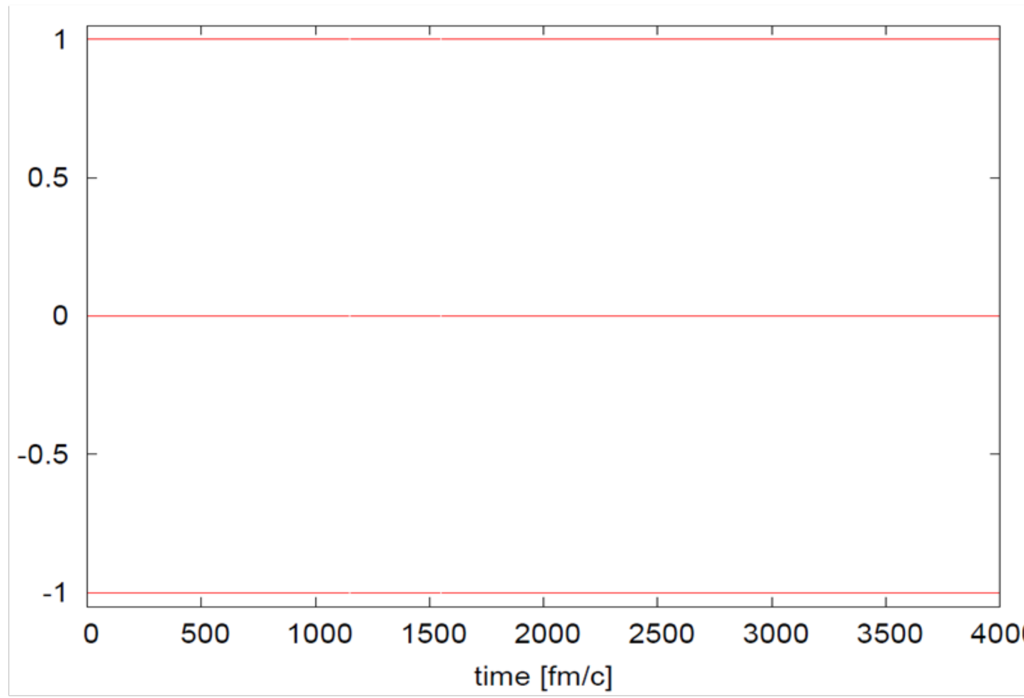
- two types of oscillations after relaxation process
- effects of pairing correlations in oscillating motions

→ put focus on the occupation probabilities of TDHFB orbitals $\boxed{\sum_i V_{ij}^* V_{ij}}$

Case 1: oscillations around Q_{20} = 85 [fm^2] (constraint Q_{20} = 170 [fm^2])



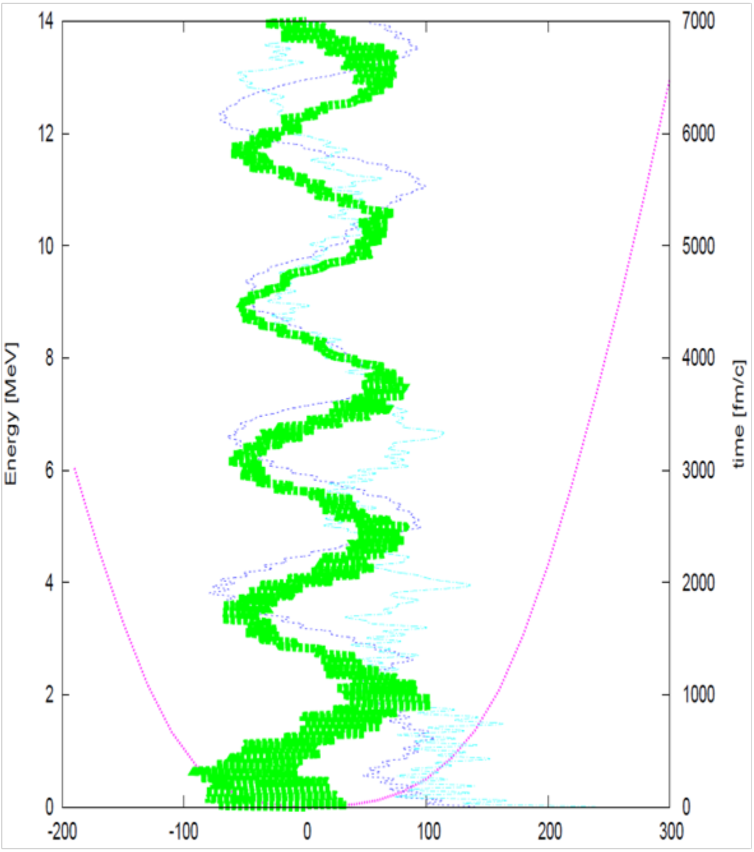
time dependence
of occupation probability (neutrons)



initial condition : Q_{20} = 170 [fm^2]
Ex = 2.56[MeV]
E_pair(proton) = - 3.55[MeV]
E_pair(neutron) = 0 [MeV]

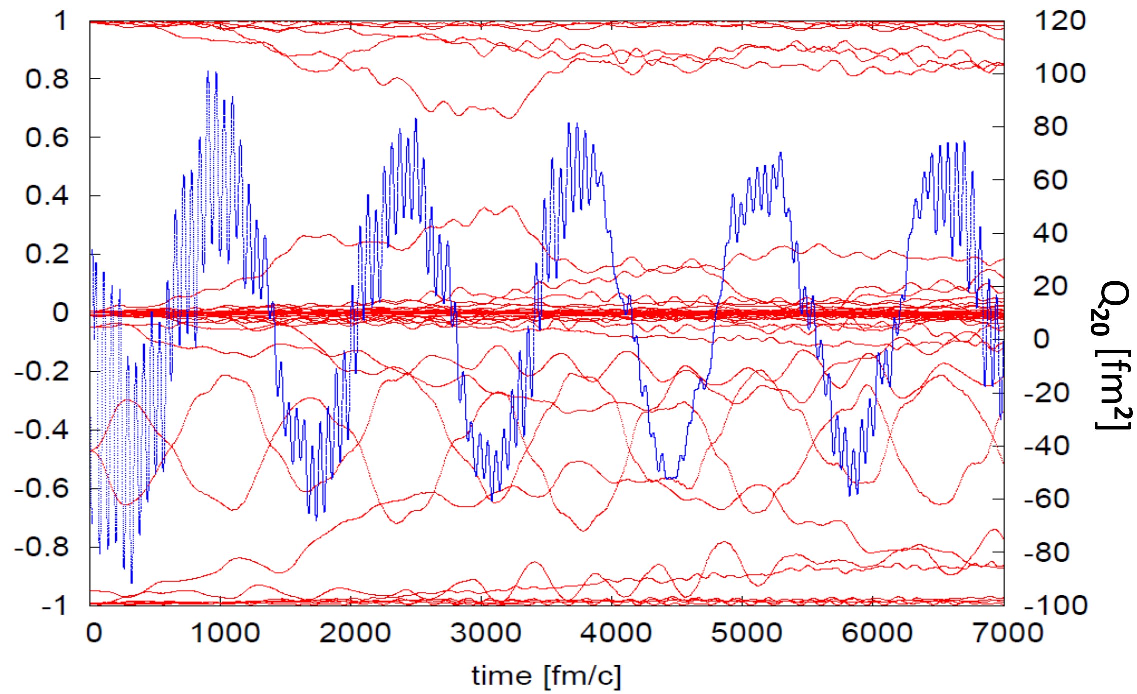
- no pairing in neutrons
→ no jump into ground state pocket (Q20 = 0[fm^2])

Case 2: oscillations around ground state (Q20 = 0 [fm^2])
(impulse type)



Q_{20} [fm^2]

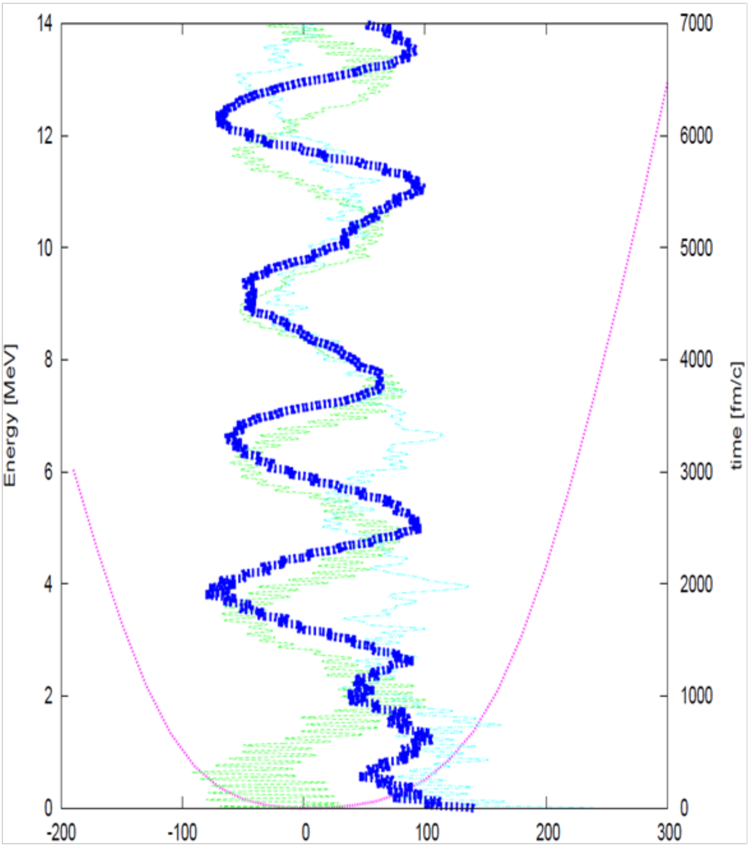
time dependence
of occupation probability (neutrons)



impulse type
Ex = 4.32[MeV]
E_pair(proton) = - 4.79 [MeV]
E_pair(neutron) = - 2.75 [MeV]

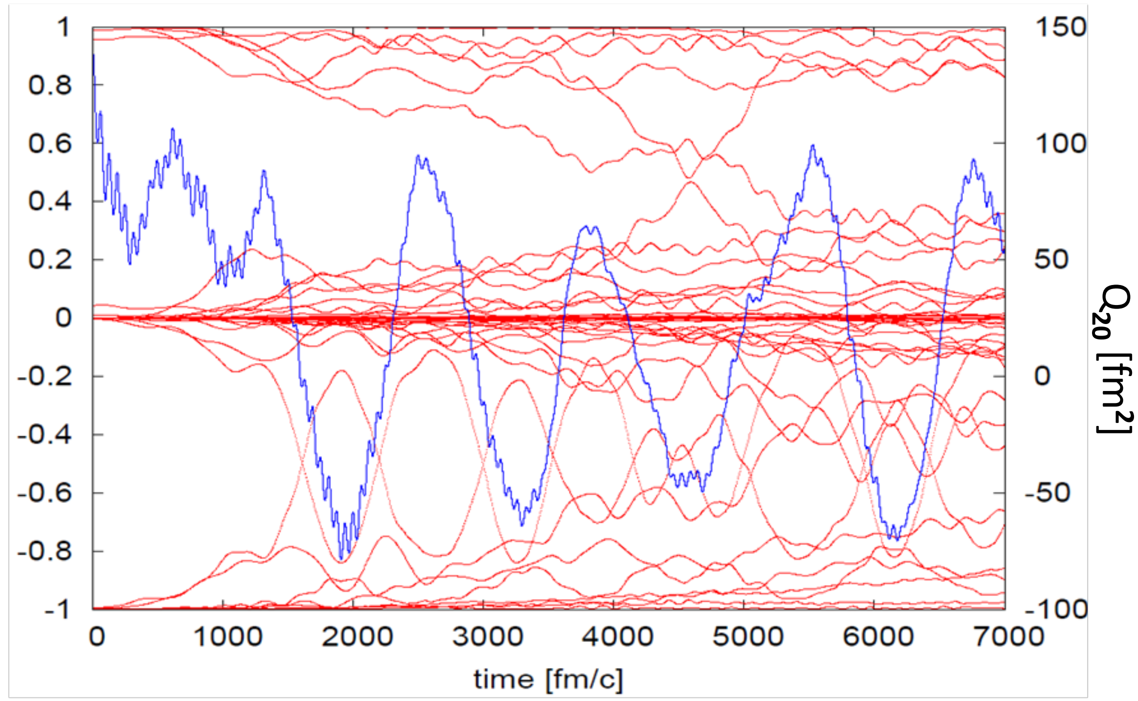
- two main trajectories
- Q_{20} oscillation ←→ seesaw in occupation probabilities

Case 3: jump into ground state pocket (constraint Q_{20} = 140 [fm^2])



Q_{20} [fm^2]

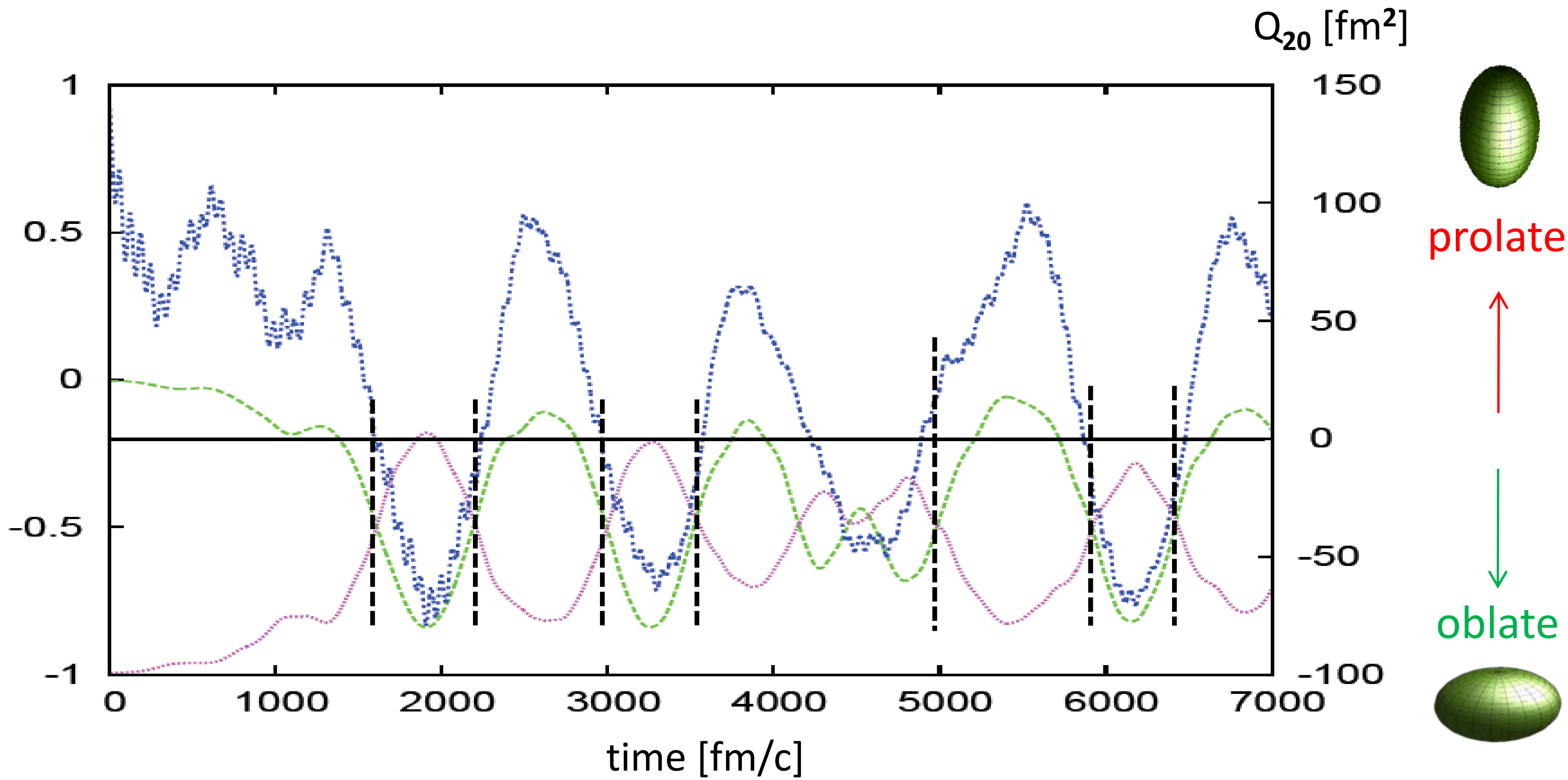
time dependence
of occupation probability (neutrons)



initial condition : Q_{20} = 140 [fm^2]
Ex = 1.37[MeV]
E_pair(proton) = - 3.27 [MeV]
E_pair(neutron) = - 0.07 [MeV]

- sudden change in occupation probability
  → Q20 oscillation jumps
- characteristic two orbitals
- in phase with Q20 oscillation

variations of occupation probabilities of two main trajectories(constrait Q_{20} = 140 [fm^2])



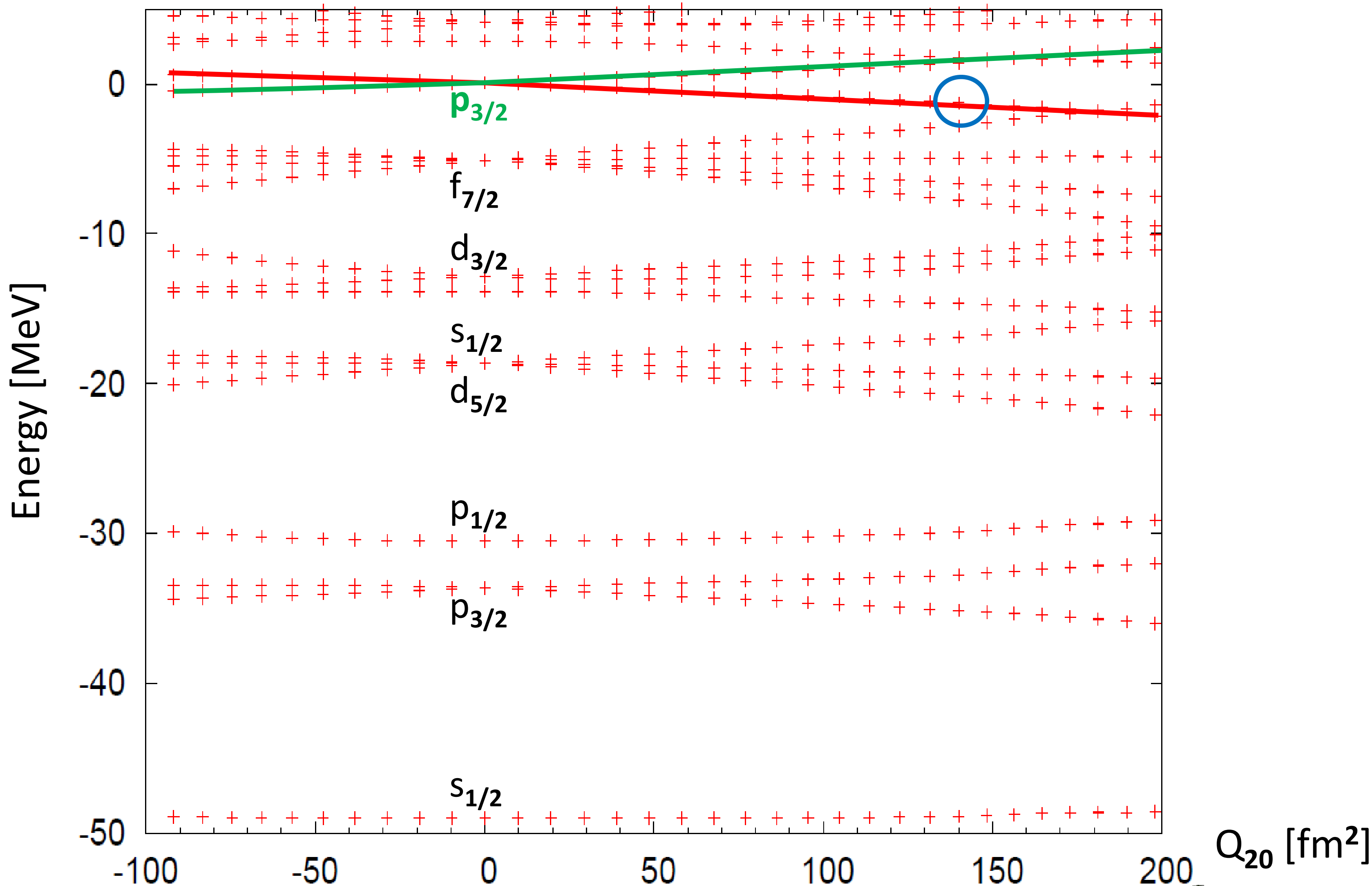
prolate side … red orbital main

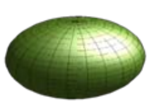
$(n_x, n_y, n_z) = (3, 0, 0)$

oblate phase … green orbital main

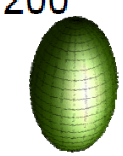
$(n_x, n_y, n_z) = (0, 3, 0) , (0, 0, 3)$

^{52}Ti (Z = 22, N = 30) one particle levels (neutrons)



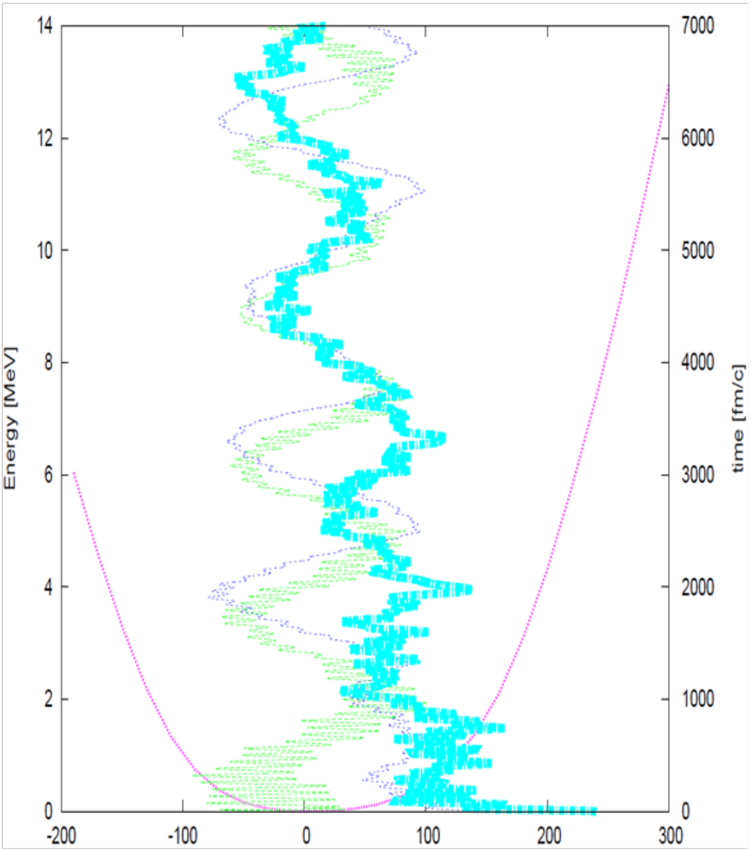


oblate ← → prolate

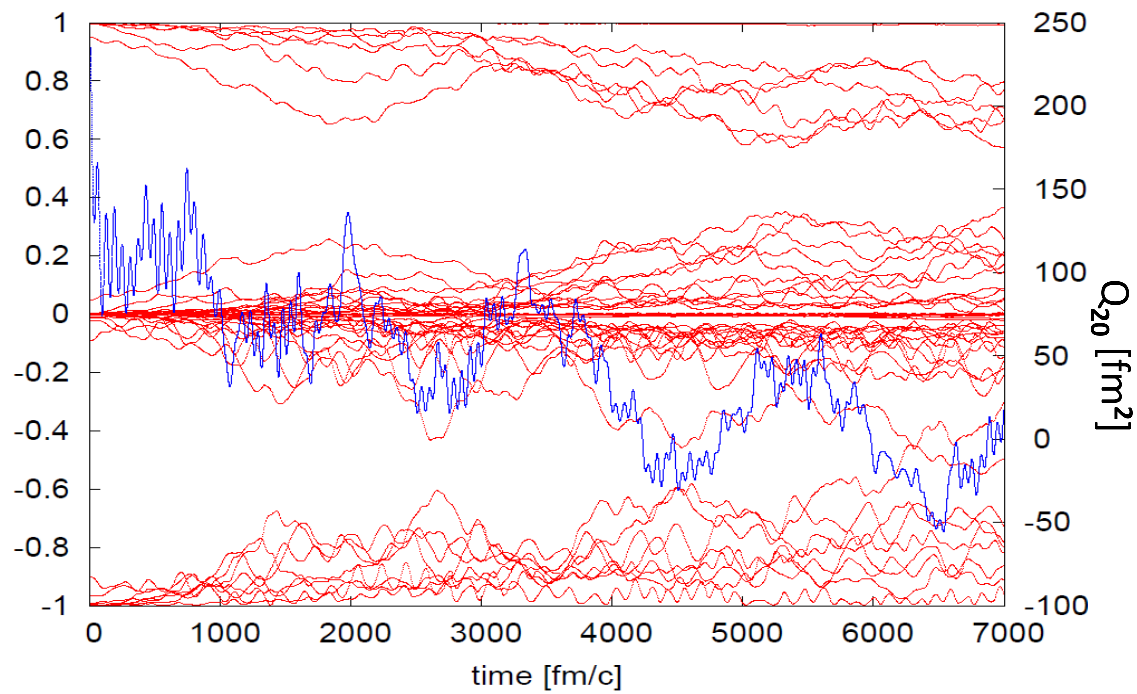


change of occupation probability ⟷ quadrupole oscillation

Case 4: slow relaxation (constraint Q_{20} = 240 [fm^2])



準粒子軌道の占有率の時間変化（中性子）



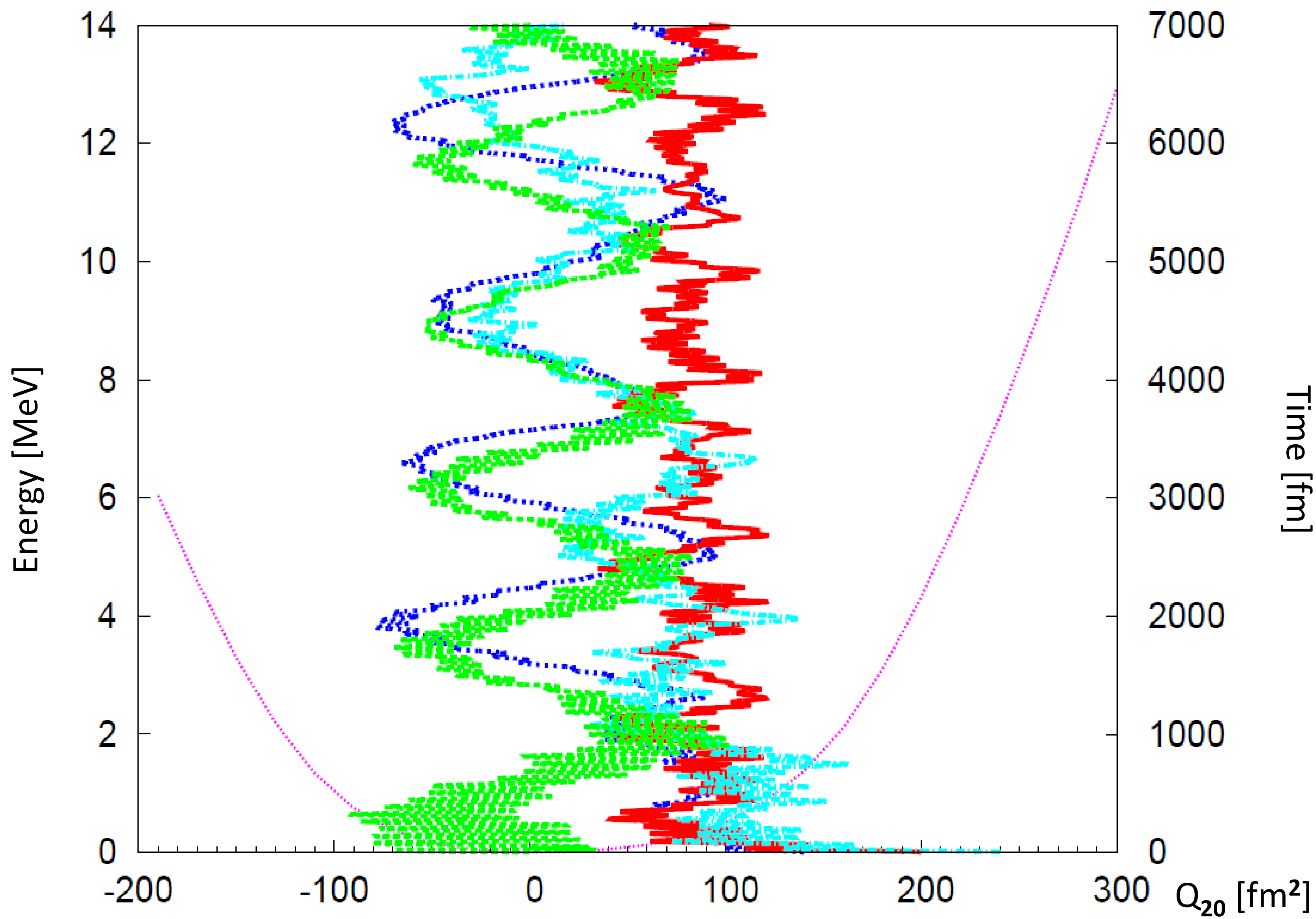
initial condition : Q_{20} = 240 [fm^2]
Ex = 7.37[MeV]
E_pair(proton) = - 4.79 [MeV]
E_pair(neutron) = - 0.89 [MeV]

slow relaxation

- occupation probabilities of many orbitals change
  → two main orbitals becomes unclear

period → OK

unsolved problem: amplitudes

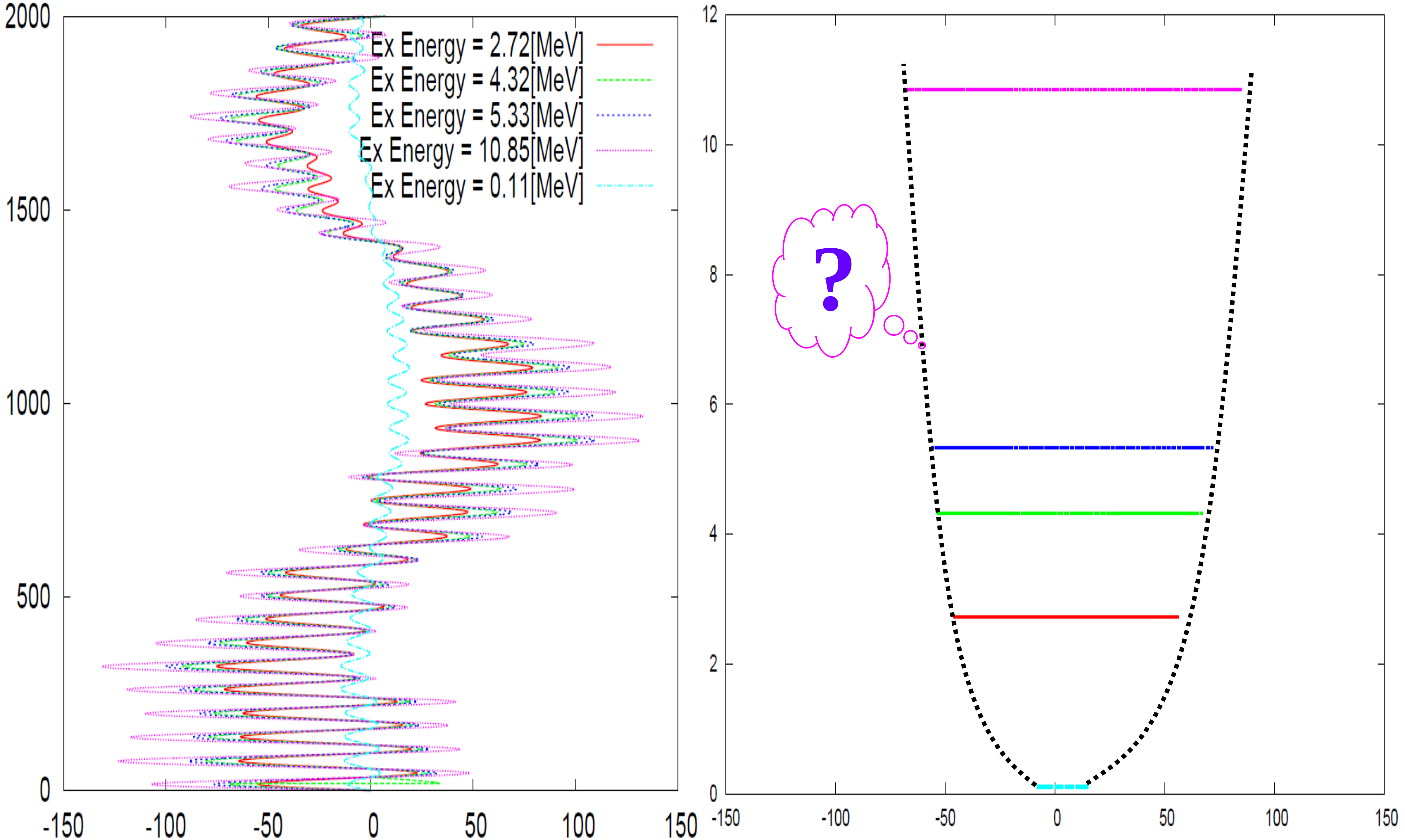


Impulse type
Ex E= 4.32[MeV]
Pairing E (p)= -4.79[MeV]
Pairing E (n)= -2.75[MeV]

Initial Q20 = 140
Ex E= 1.37[MeV]
Pairing E (p)=-3.27[MeV]
Pairing E (n)=-0.07[MeV]

Initial Q20 = 200
Ex E=4.32 [MeV]
Pairing E (p)=-4.19[MeV]
Pairing E (n)=0 [MeV]

Initial Q20 = 240
Ex E= 7.37[MeV]
Pairing E (p)=-4.79[MeV]
Pairing E (n)=-0.89[MeV]



Amplitudes of slow oscillations with excitation energy from 2.72 to 10.85 [MeV] vary very slowly.

Summary

1. Intermediate amplitude collective oscillations are calculated in terms of TDHFB with Gogny interaction.

2. Pairing correlation easily affects the oscillations:
   * center of oscillation
   * period, amplitude
   * relaxation time

3. occupation probability changes continuously
   ←→ quantum numbers are discrete
   Oscillation with long period may easily come out.

4. improvements in future :
   * better basis
     → Gogny TDHFB with GEM, cylindrical HO basis, ...
   * connections with microscopic analysis such as AdSCC.