MICROSCOPIC DESCRIPTION OF NEUTRINO-NUCLEUS REACTIONS

Cristina VOLPE
(IPN, Orsay)

- Motivation
- Theoretical aspects
- Results : $\nu + {}^{12}C$
  $\nu + {}^{208}Pb$

WHY ν-NUCLEI REACTIONS ?

- ➯ They may play a rôle in astrophysical processes such as nucleosynthesis.

- ➯ Nuclei are used as detectors in experiments on neutrinos

! To study ν PROPERTIES (EX. MASS)

TO STUDY STARS (EX. SUN, SUPERNOVAE) !

Evidence for oscillations

- $\nu_i \to \nu_j$ $\qquad \nu_\ell + X \to Y + \ell$ (A) REACTION TO DETECT NEUTRINOS
- $\boxed{N^{(A)}_{\text{MEASURED}} = N^{(A)}_{\text{EXPECTED}}}$ ➤ $P(\nu_i \to \nu_j) = 0$

  EVENTS

  <u>NO OSCILLATIONS</u>

- $\nu_i \to (\nu_j)$

$$\boxed{N^{(A)}_{\text{MEA}} = N^{(A)}_{\text{EXP}}\left(1 + P_{\nu_i \to \nu_j}\right)}$$

$$N^{(A)}_{\text{EXP}} = \varepsilon_{(A)} \cdot \Phi_{\nu_i} \cdot \sigma^{(A)}$$

➤ $$P_{\nu_i \to \nu_j} = \frac{N^{(A)}_{\text{MEA}}}{\varepsilon \Phi \sigma^{(A)}} - 1$$

<u>WITH OSCILLATIONS</u>

➡ THE INTERPRETATION OF SOME EXPERIMENTS DIRECTLY RELIES ON THE CROSS SECTION $\sigma^{(A)}$!

ν from supernovae explosion

- events from SN1987A.

- NEW PROJECTS!
  Lead Astronomical Neutrino Detector (LAND)
  Observatory for Multiflavour Neutrino Interactions from Galactic Supernovae (OMNIS)
  - ν-^{208}Pb reactions should be used to detect neutrinos.
  - There are no experimental results on ν-^{208}Pb cross sections.

➡ THEORETICAL ESTIMATES OF ν-NUCLEI REACTION CROSS SECTIONS ARE REQUIRED.

TWO RECENT STUDIES

$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$

important for the interpretation of the LSND experiments on neutrino oscillations.

?

THE PROBLEM :
A significant discrepancy between experiment and theory (by a factor 4 !)

$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi + e^-$

necessary to evaluate the feasibility of new detectors for supernovae neutrinos.

THE PROBLEM :
No experimental data, need of different theoretical estimates.

?

THEORETICAL ASPECTS:
The effective hamiltonian

- The V-A interaction hamiltonian:

$$\hat{H}^{V\text{-}A} = G\, J^{\mu}_{(H)} \cdot J^{(L)\dagger}_{\mu} + h.c.$$

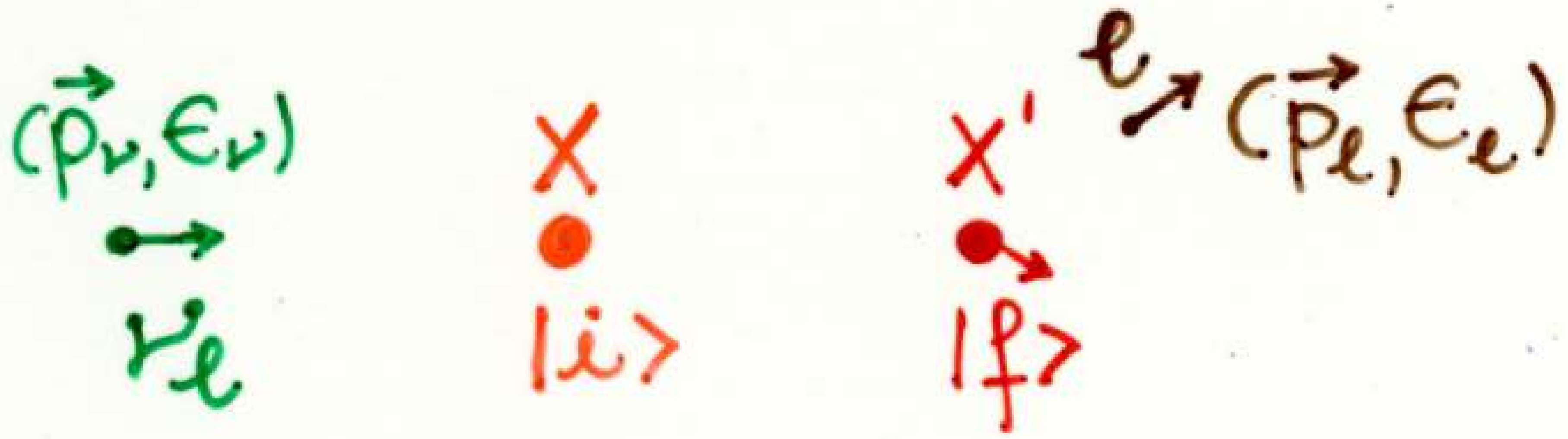
$J^{\mu}_{(H)}$ - hadronic current

$J^{\mu}_{(L)}$ - leptonic current

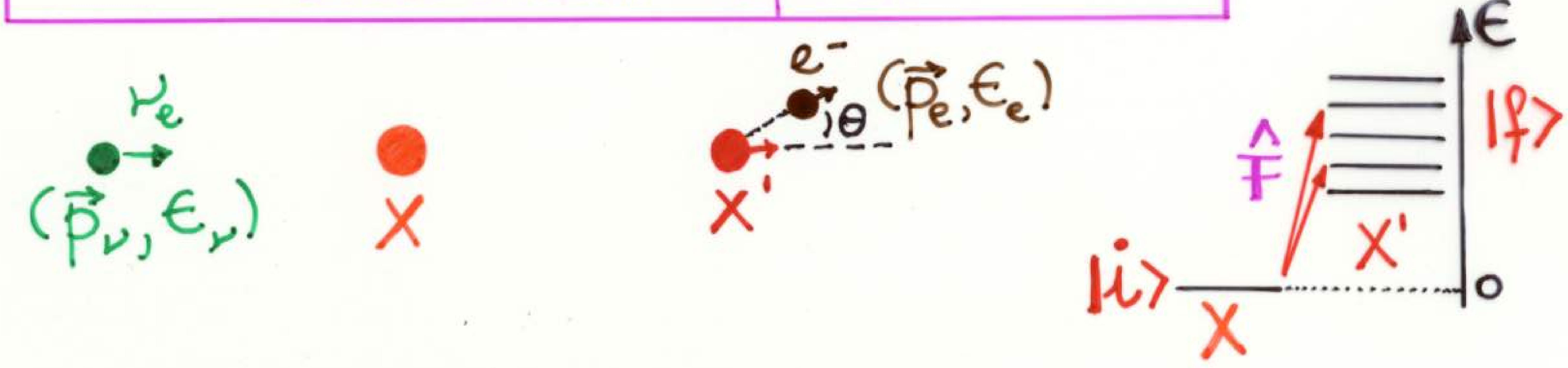
- Applying the Foldy-Wouthuysen (FW) transformation to get the non-relativistic hadronic hamiltonian.

- Using perturbation theory:

$$\sigma(\epsilon_\nu) = (2\pi)^4 \int d^3p_\ell\, \delta(\epsilon_\ell + \epsilon_f - \epsilon_\nu - \epsilon_i)\, |\langle \ell; f|\hat{H}|\nu; i\rangle|^2$$



ν- NUCLEI REACTION CROSS SECTIONS: Theoretical aspects



- $$\sigma(\epsilon_\nu) = \frac{G^2}{2\pi}\cos^2\theta_c \sum_f \left[\int (d\cos\theta)\, M_f\right] p_e \epsilon_e$$

- $$M_f = |\langle f|\hat{F}|i\rangle|^2$$

$$|\langle f|\sum_k j_\ell(qr_k)\, Y_\ell(\hat{r}_k)\, t_\pm(k)|i\rangle|^2$$

FERMI (ISOSPIN) TYPE TRANSITIONS

$$|\langle f|\sum_k j_\ell(qr_k)\, [Y_\ell(\hat{r}_k)\times\sigma]^{(K)}\, t_\pm(k)|i\rangle|^2$$

GAMOW-TELLER (SPIN-ISOSPIN) TRANSITIONS

WE NEED ISOSPIN AND SPIN-ISOSPIN TRANSITION PROBABILITIES.

Microscopic approaches

- We start with a mean field approximation:

- We create 1particle-1hole (1p-1h) excitations:

  - and include the particle-hole residual interaction: ⇒ RANDOM PHASE APPROXIMATION (RPA)
  - with pairing correlations: ⇒ QRPA

- We create 2p-2h, 3p-3h, … and include residual interactions: ⇒ SHELL MODEL (SM)

⇒ RPA, QRPA AND SM ARE USED TO EVALUATE TRANSITION PROBABILITIES.

Weak processes in nuclei

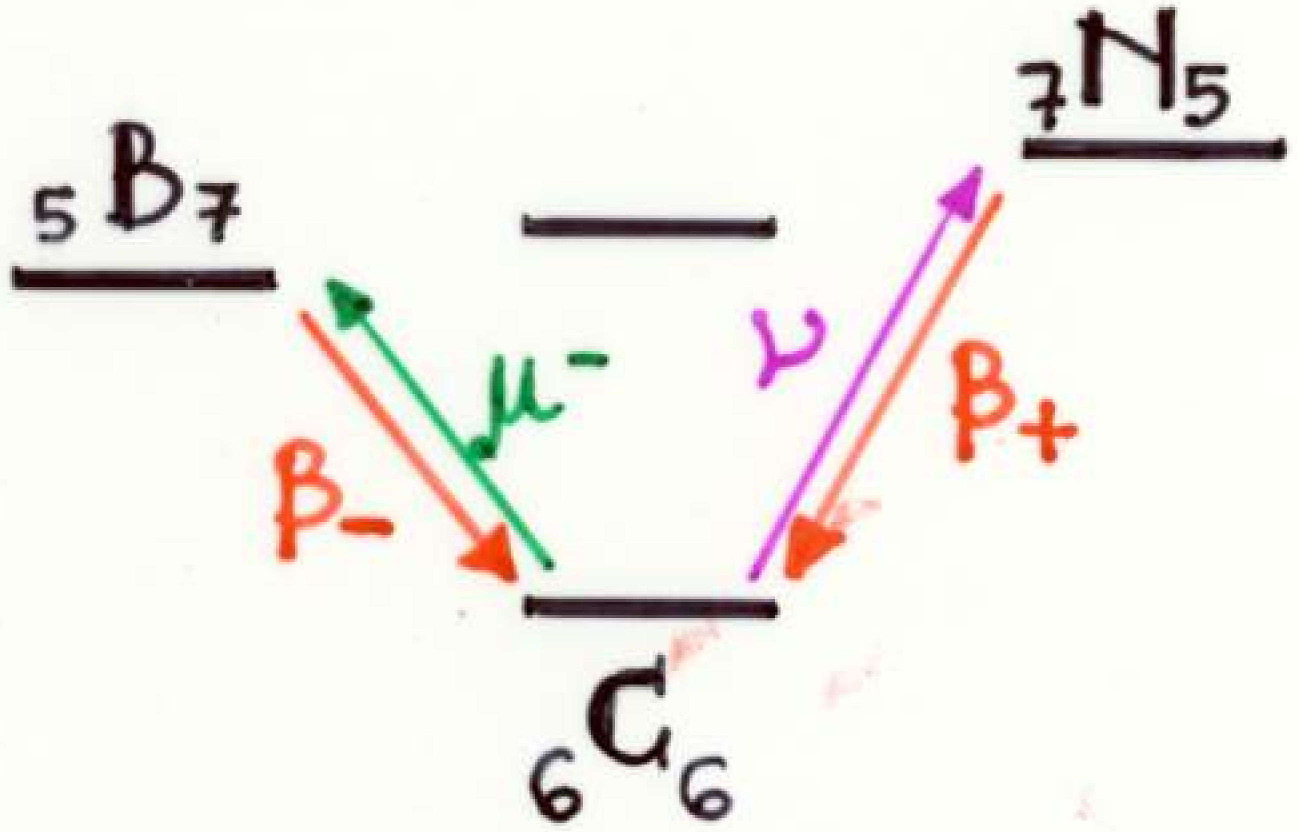
- $\nu_\ell + (Z,N) \rightarrow (Z+1,N-1) + \ell^-$ $\ell = e,\mu$ ν_ℓ-CAPTURE

  $(Z,N) \rightarrow (Z+1,N-1) + e^- + \bar{\nu}_e$ β-DECAY

  $\ell^- + (Z,N) \rightarrow (Z-1,N+1) + \nu_\ell$ ℓ-CAPTURE

  - EXAMPLE

    $A = 12$

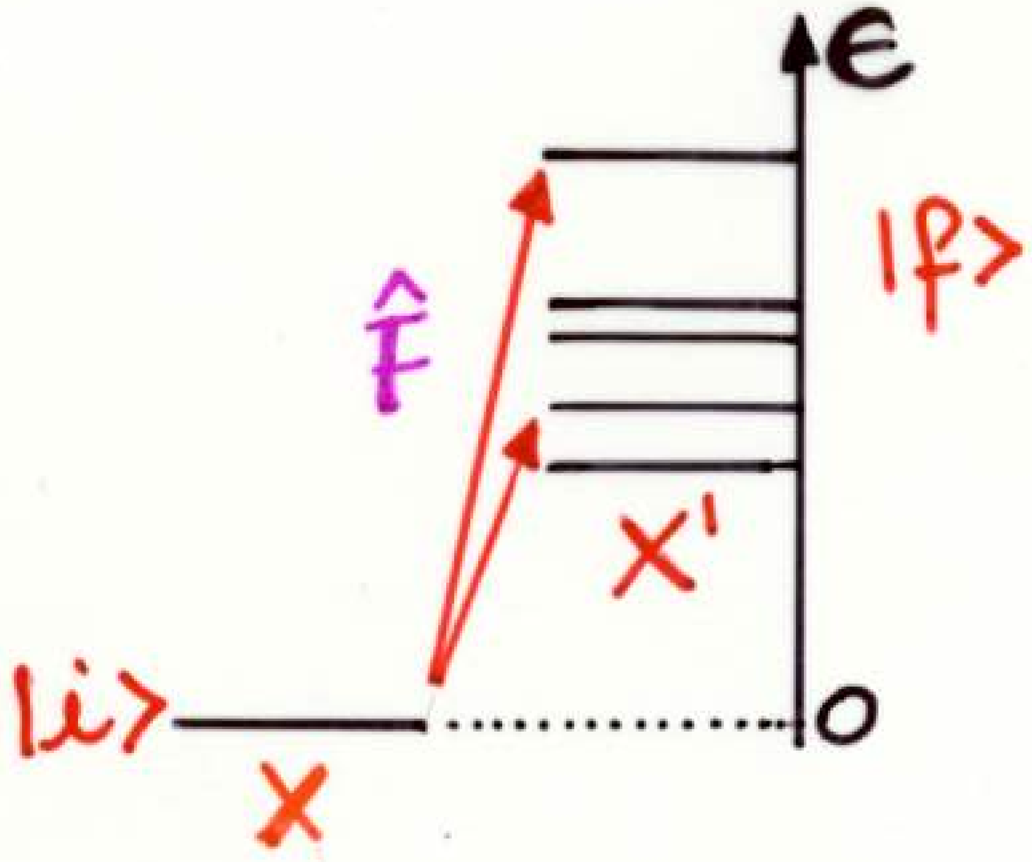


➜ A TEST OF THE TRANSITION PROBABILITIES.

What are the difficulties?

- The approximations inherent to the nuclear structure models can make it difficult to take into account all the nuclear structure aspects which can significantly affect the cross sections.

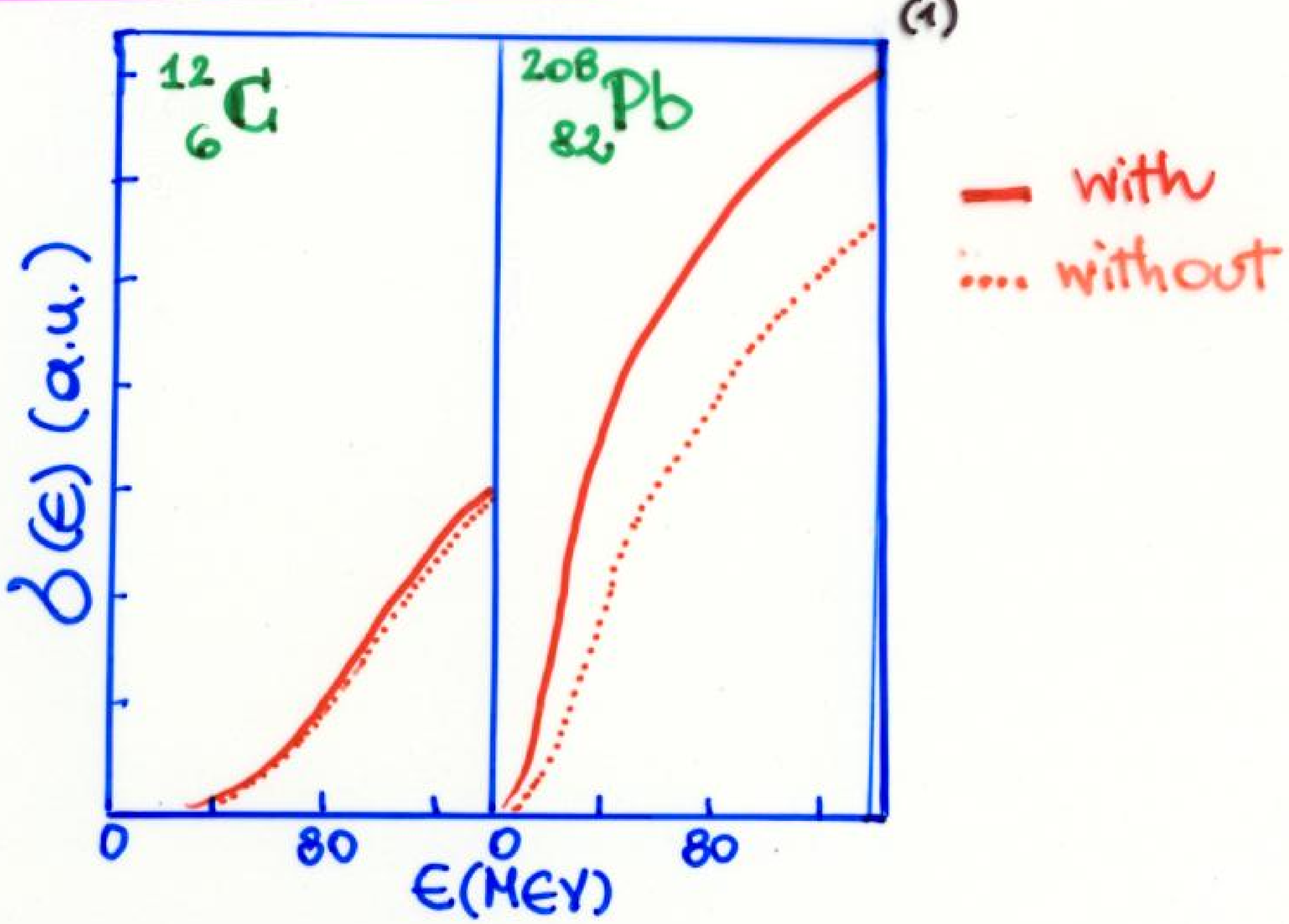
- The energy transferred to the nucleus is quite large (~ 40 MeV). We need large model spaces to describe high energy states excited in the final nucleus.
We have to make truncations of the model space.



TO GO BEYOND THESE APPROXIMATIONS OR/AND) REALIZE LARGE SCALE CALCULATIONS IS A REAL CHALLENGE!

TWO RECENT STUDIES:
RESULTS ON $\nu_e + {}^{208}Pb \to {}^{208}Bi + e^-$

Coulomb corrections



(1)

- The electromagnetic interaction of the outgoing charged lepton with the final nucleus is very important for large Z nuclei.
- Two approximate treatments:
  - Fermi function $F(Z,\epsilon_e)$:

$\sigma(\epsilon_e)F(Z,\epsilon_e)$

F is the Coulomb wave to the free wave at the nuclear surface.

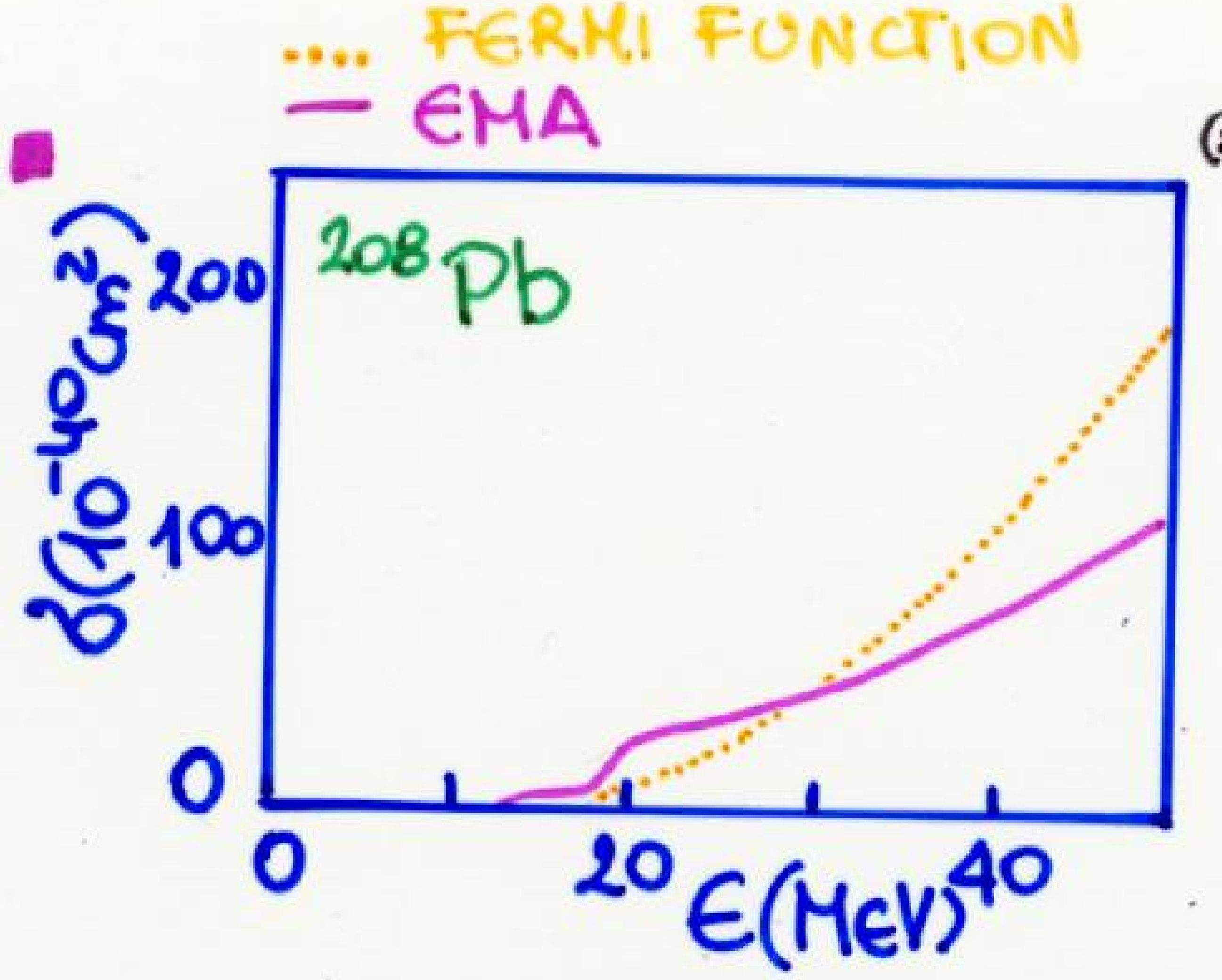
($K_\ell \cdot R \ll 1$, K_ℓ is the lepton momentum, R the nuclear radius)

  - Effective Momentum Approximation (EMA):

$(\epsilon_\ell, \vec{K}_\ell) \to (\epsilon_\ell^{eff} = \epsilon_\ell - V(0), |\vec{K}_\ell^{eff}| = \sqrt{\epsilon_\ell^{eff\,2} - M^2})$

---

(1) J. Engel, Phys. Rev. C57 (1998) 2004.

- 

(*)

(*) C. Volpe et al., submitted to Phys. Rev. C.

WE HAVE EMPHASIZED THAT EMA HAS TO BE USED WHEN $K_e R \gtrsim 1$.

- $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$ DECAY-AT-REST (DAR)

$\langle\sigma\rangle_\phi = \int \sigma(E_\nu)\,\phi(E_\nu)\,dE_\nu$ $\phi(E_\nu)$-flux

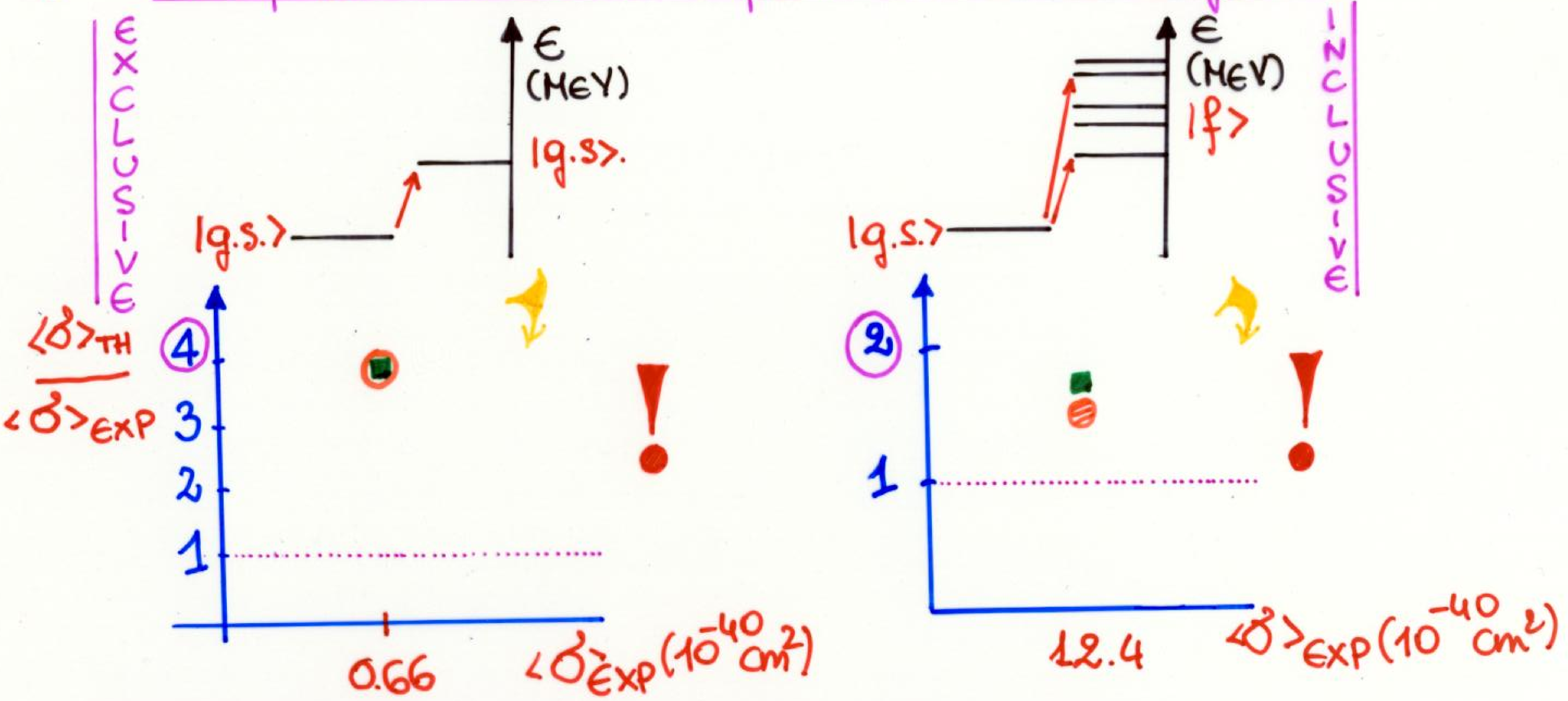
flux-averaged cross sections.

THE USE OF FERMI OR EMA CORRECTIONS MODIFIES $\langle\sigma\rangle_\phi^{DAR}$ BY 20-30%.

$\nu_\mu + {}^{12}C \to {}^{12}N + \mu^-$: THE PROBLEM

$\pi^+ \to \mu^+ + \nu_\mu$
DECAY-IN-FLIGHT

Comparison between experiment and theory (RPA)



SIGNIFICANT DISCREPANCIES ON $\langle\sigma\rangle_{TH}/\langle\sigma\rangle_{EXP}$ FOR $\nu + {}^{12}C$ REACTION.

■ C. Volpe et. al., Phys. Rev C 62 (2000) 015501.

● E. Kolbe, K. Langanke, P. Vogel, Phys. Rev C 49 (1994) 1122.

Relation with the LSND experiments on neutrino oscillations

- The neutrino flux used in one experiment is : $\pi^+ \to \mu^+ + \boxed{\nu_\mu}$ DECAY-IN-FLIGHT
- It is an appearance experiment :

$$\nu_\mu \to \boxed{\nu_e}$$

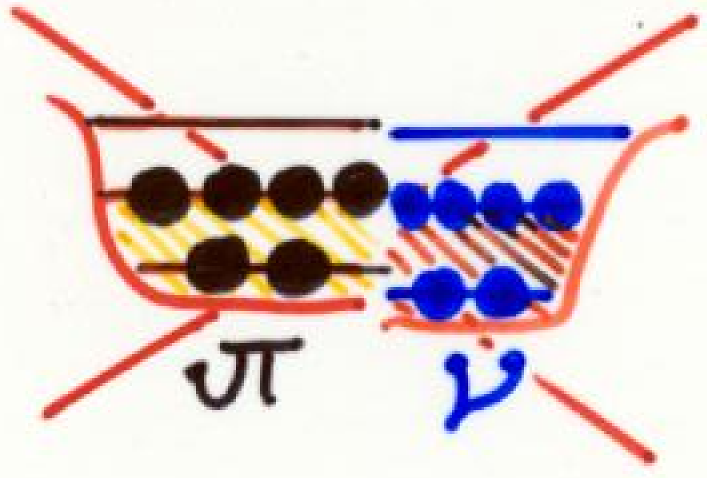
  - Neutrinos are detected through: $\boxed{\nu_e} + {}^{12}C \to {}^{12}N + e^-$
  - A positive oscillation signal is found.
  - The detector used is the same than the one used to measure $\nu_\mu + {}^{12}C \to {}^{12}N + \mu^-$ for which there are discrepancies between experiment and theory.

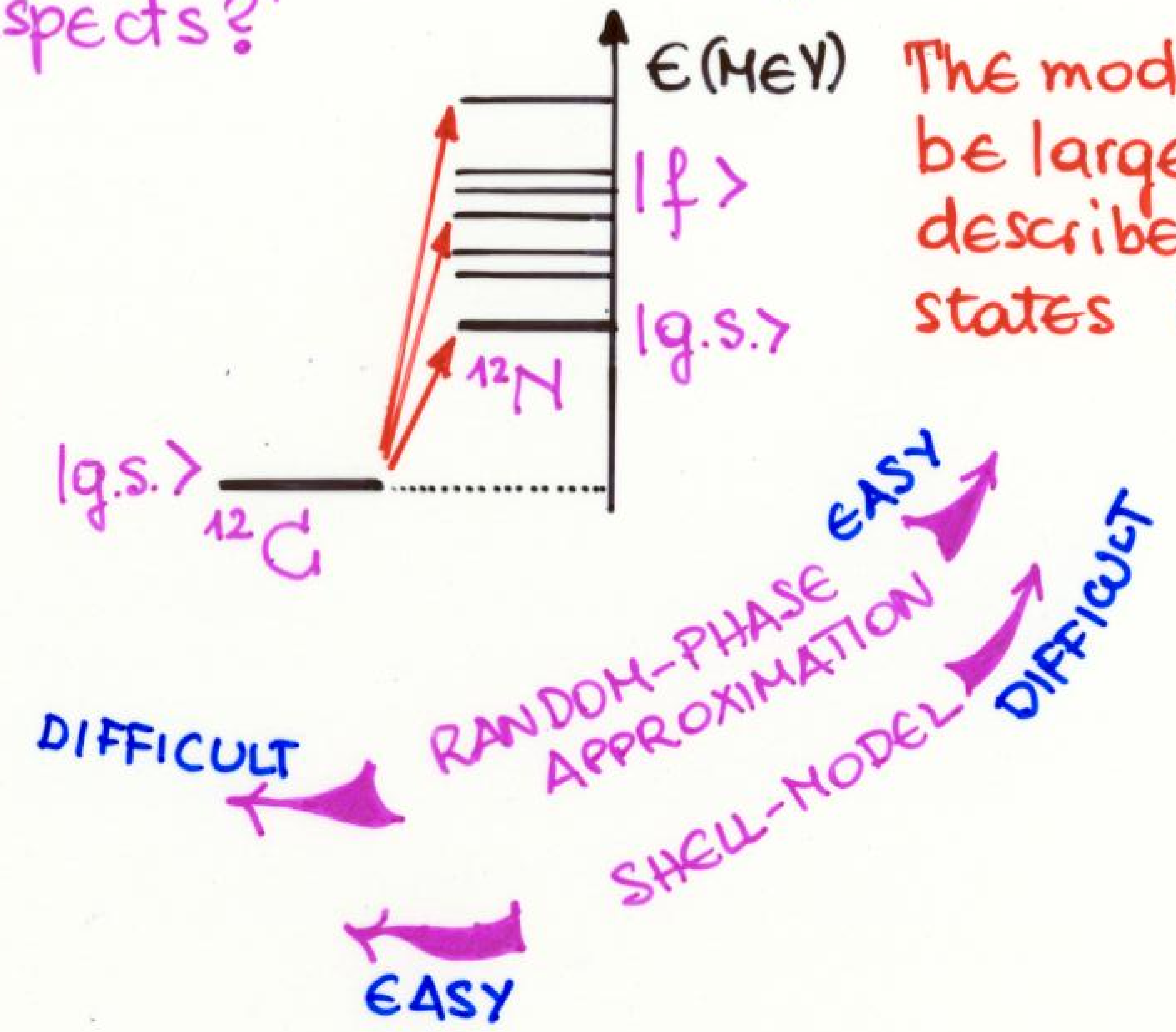
➡ BECAUSE THE ORIGIN OF THE DISCREPANCY WAS NOT UNDERSTOOD, THIS CAST SOME DOUBT ON THE OSCILLATION EXPERIMENT RESULTS.

The idea

- Could the discrepancies come from nuclear structure aspects?

In fact, ^{12}C is not a good closed subshell nucleus:





The model space must be large enough to describe high energy states in ^{12}N.

The improvements

- Within RPA, we have tried to improve the g.s. description of ^{12}C, by going beyond the "standard" approximation.
- Within SM, we have realized large scale calculations.

Present status of the problem

$\nu_\mu + {}^{12}C \to {}^{12}N + \mu^-$ with $\pi^+ \to \mu^+ + \nu_\mu$

DECAY-IN-FLIGHT

➡ THE THEORETICAL CROSS SECTIONS ARE VERY CLOSE TO THE EXPERIMENTAL VALUES.

■ RPA	E.Kolbe, K.Langanke, P.Vogel, Phys.Rev C49 (1994) 1122.
🟩 RPA (f.o.)	E.Kolbe, K.Langanke, P.Vogel, Nucl.Phys.A652 (1999) 91.
▨ RPA SM ●	C.Volpe, N.Auerbach., G.Colò, T.Suzuki, N.Van Giai, Phys.Rev C62 (2000) 015501.
SM ●	A.C.Hayes, I.S.Towner, Phys.Rev C61 (2000) 0044603.

CONCLUSIONS

- A detailed knowledge of ν-nuclei reaction cross sections is necessary to evaluate the feasibility of new detectors and interpret some of the experiments on neutrino oscillations.

$\nu + {}^{12}C$

- For the problem concerning $\nu + {}^{12}C$, we have realized large scale calculations and gone beyond "standard" approximations to show that the significant discrepancies between experiment and theory are due to nuclear structure aspects.

$\nu + {}^{208}Pb$

- We have shown that the use of different approximations to treat Coulomb corrections modifies the reaction cross section by 20-30%.

C. Volpe (IPN, orsay)
N. Auerbach (Tel Aviv U)
G. Colò (Milano U.)
N. Van Giai (IPN, orsay)