Cluster Effective Field Theory and nuclear reactions

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Introduction: cluster EFT

(1) Energy scales:
Around a given energy, below a break-up energy or a resonant energy, one may treat a nucleus as an elementary-like field.

(2) Expansion scheme:
One constructs an effective Lagrangian, which respects to symmetry requirement, and perturbatively expands it in power of external momenta.

(3) Low energy constants:
Coefficients appear in the effective Lagrangian can be determined from microscopic nuclear theory or fitted to experimental data.

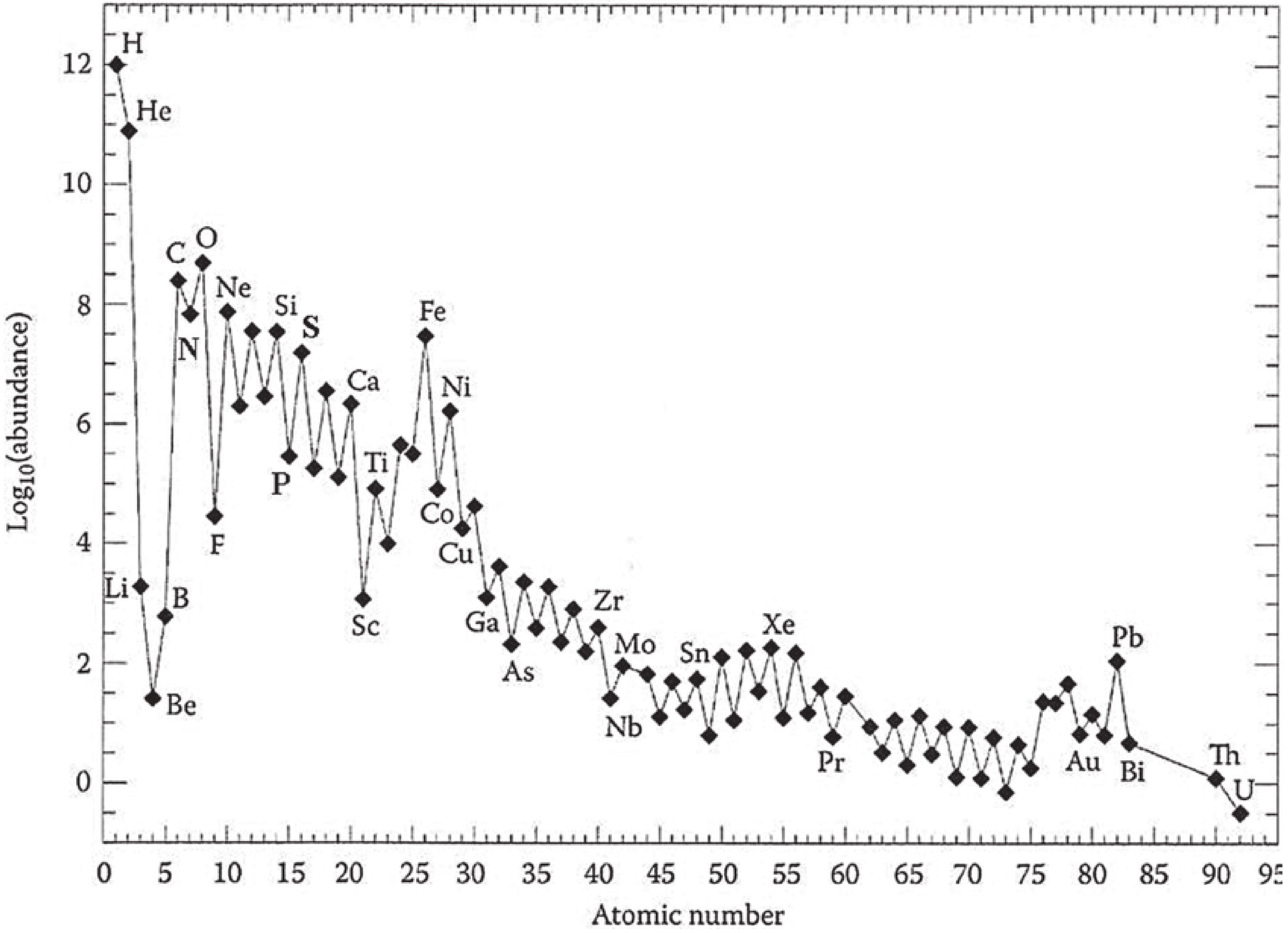
- We considered nuclear reactions related to radiative α capture on ^{12}C:
  1) Elastic alpha-carbon-12 scattering,
  2) Radiative alpha capture on carbon-12 via E1 transition,
  3) Beta delayed alpha emission from nitrogen-16

Outline of the talk

- Introduction
- Basics of nitrogen-16 beta decay and motivation
- Formalism
- Numerical results
- Discussion and future plan

Introduction

- Average cosmic abundance of the elements
- $^{12}C/^{16}O$ ratio is determined by $^{12}C(\alpha,\gamma)^{16}O$



- E1 and E2 transitions of $^{12}C(\alpha,\gamma)^{16}O$ are dominant
- The E1 transition is constrained by β delayed α emission from ^{16}N

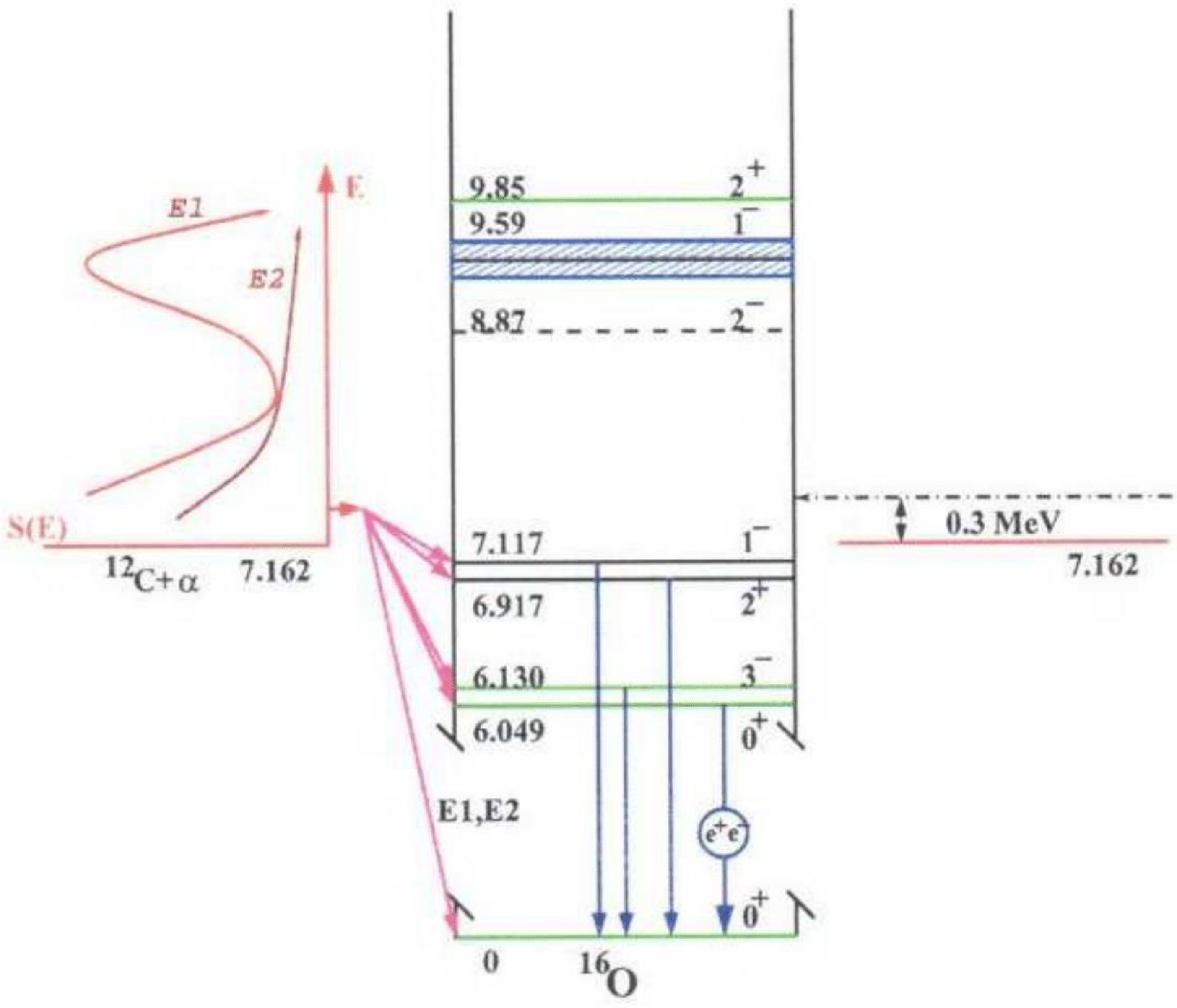
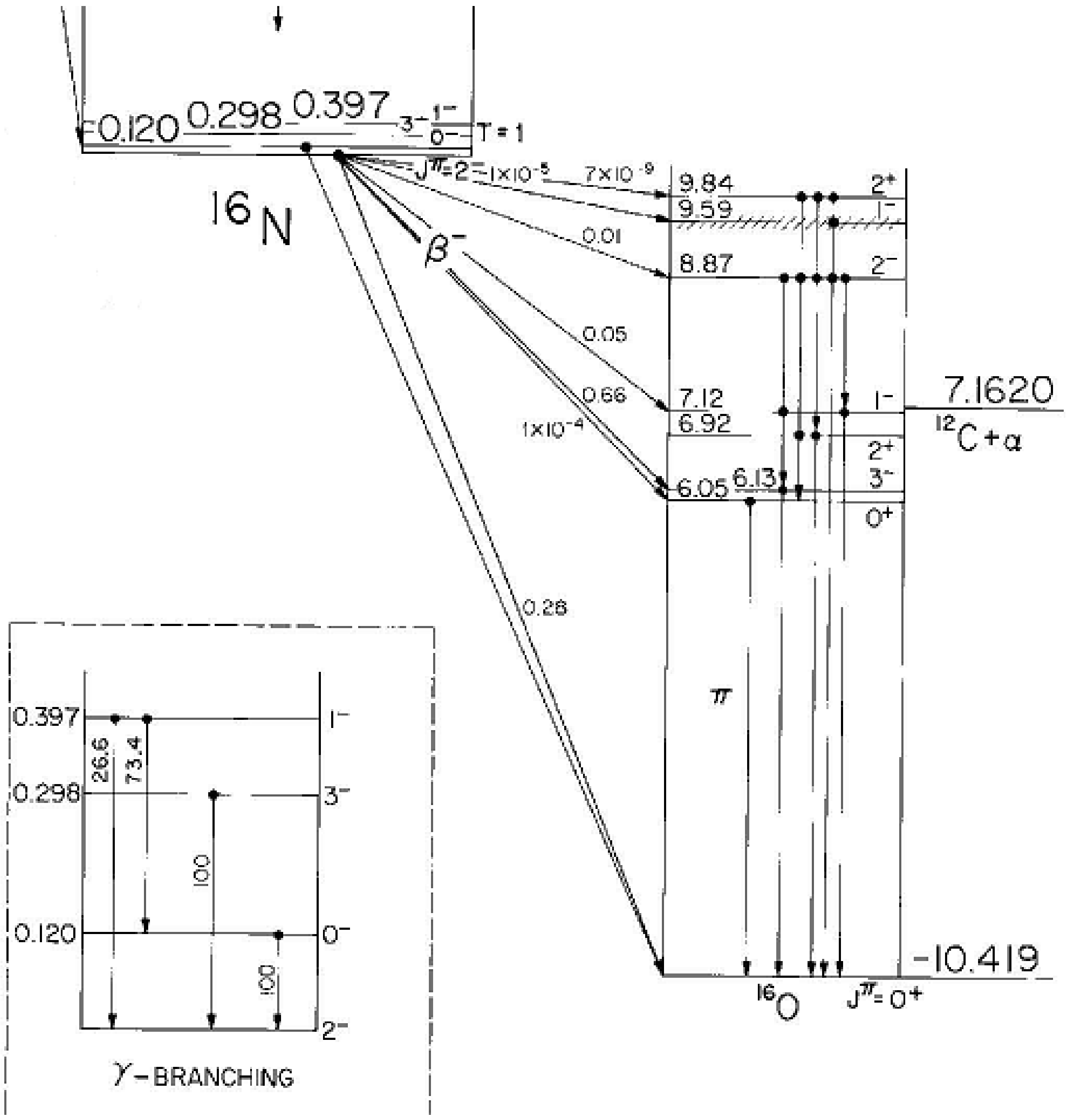


Fig. 1. ^{16}O states relevant to the $^{12}C(\alpha,\gamma)^{16}O$ reaction.

Basics of nitrogen-16 beta decay

- Beta decay from nitrogen-16
  Nitrogen-14,15: stable nuclei
  Nitrogen-16 decays through Gamow-Teller transition
  from 2^- ground state to some states of oxygen-16.
  half-lifetime 7.13 ± 0.02 sec
- Beta delayed alpha emission from nitrogen-16
  $^{16}N \rightarrow e^- + \nu + \alpha + {}^{12}C$
  branching ratio, $(1.59 \pm 0.06) \times 10^{-5}$
  p- and f-waves dominant for alpha and carbon-12 system



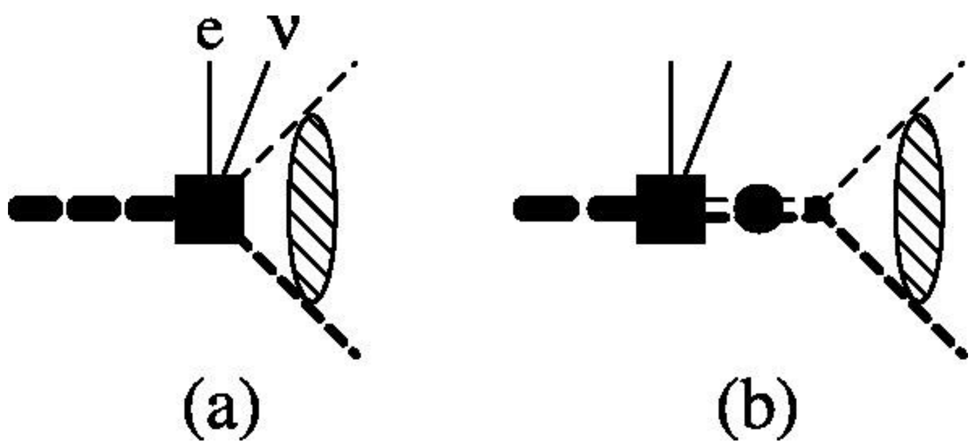
0.120
0.298
0.397
3⁻
1⁻
0⁻
T = 1
J^π = 2⁻
1×10⁻⁵
7×10⁻⁹
16N
β⁻
0.01
0.05
0.66
1×10⁻⁴
0.26
9.84
9.59
8.87
7.12
6.92
6.13
6.05
2⁺
1⁻
2⁻
1⁻
2⁺
3⁻
0⁺
7.1620
12C + α
π
-10.419
16O
J^π = 0⁺
0.397
0.298
0.120
26.6
73.4
100
100
1⁻
3⁻
0⁻
2⁻
γ - BRANCHING

Motivation of the work

- A secondary peak of the alpha energy distribution from beta delayed alpha emission from nitrogen-16 is important to determine the ANC (or reduced width) for the subthreshold l=1 state of oxygen-16 for the estimate of the S_{E1} factor.
- In R-matrix analysis, the secondary peak is reproduced from an interference of the l=1 level states including so-called "background levels."
- In EFT, there is no interference between the l=1 level states because they are represented in terms of a single dressed oxygen-16 propagator.
- Q: How can I understand the situation ?

Formalism

- Diagrams

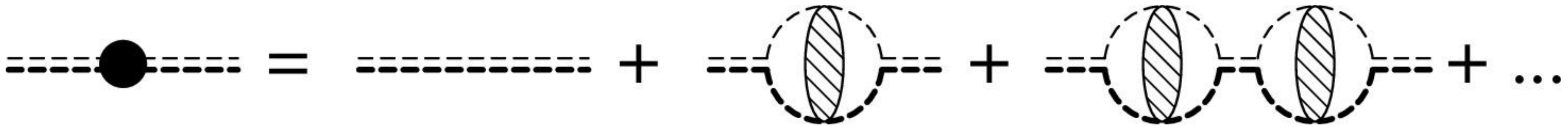


- Reduced amplitudes

$$\tilde{A}_1 = C_a^{(l=1)} + D_a^{(l=1)}\frac{p^2}{\mu^2} + \frac{C_b^{(l=1)} + D_b^{(l=1)}\frac{p^2}{m_O^2}}{K_1(p) - 2\kappa H_1(p)},$$

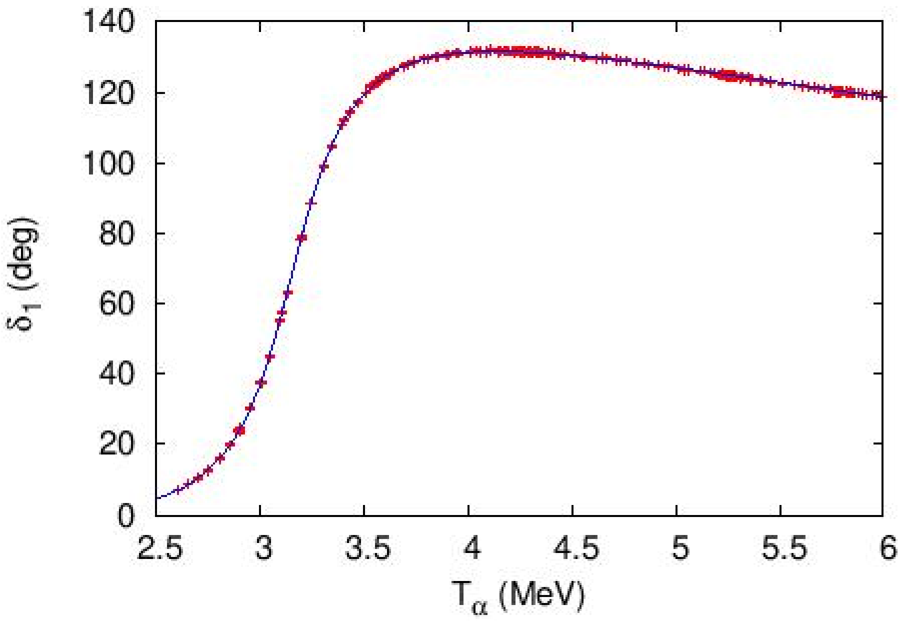
$$\tilde{A}_3 = C_a^{(l=3)} + \frac{C_b^{(l=3)}}{K_3(p) - 2\kappa H_3(p)},$$

- Dressed oxygen-16 propagator



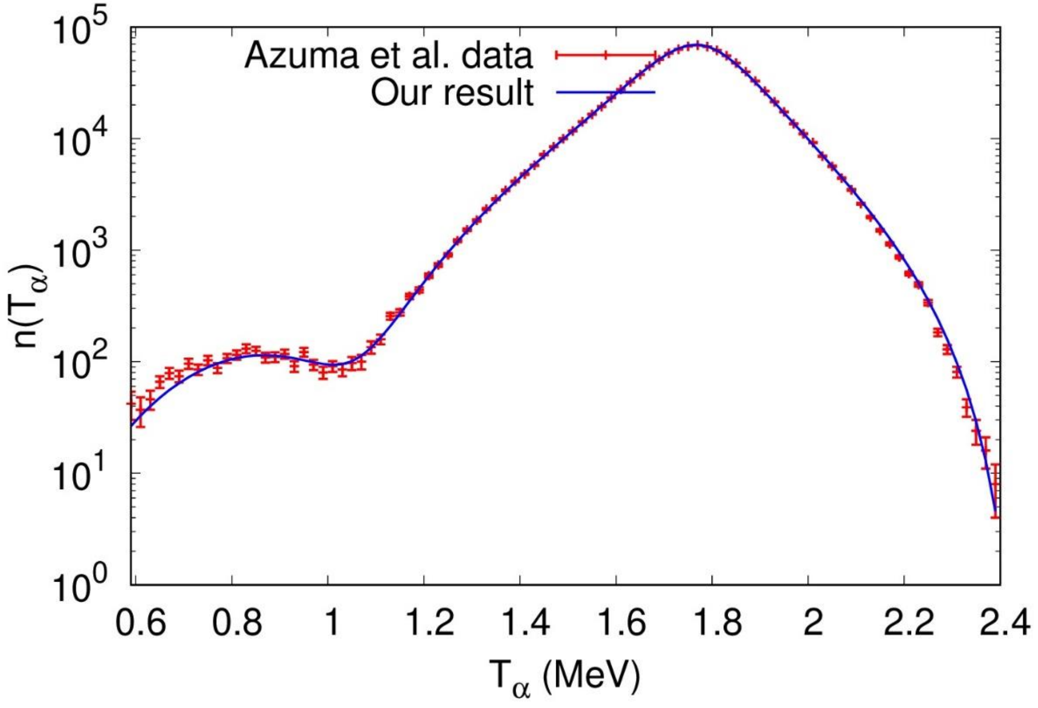
- Phase shift for l=1
  (elastic scattering data)

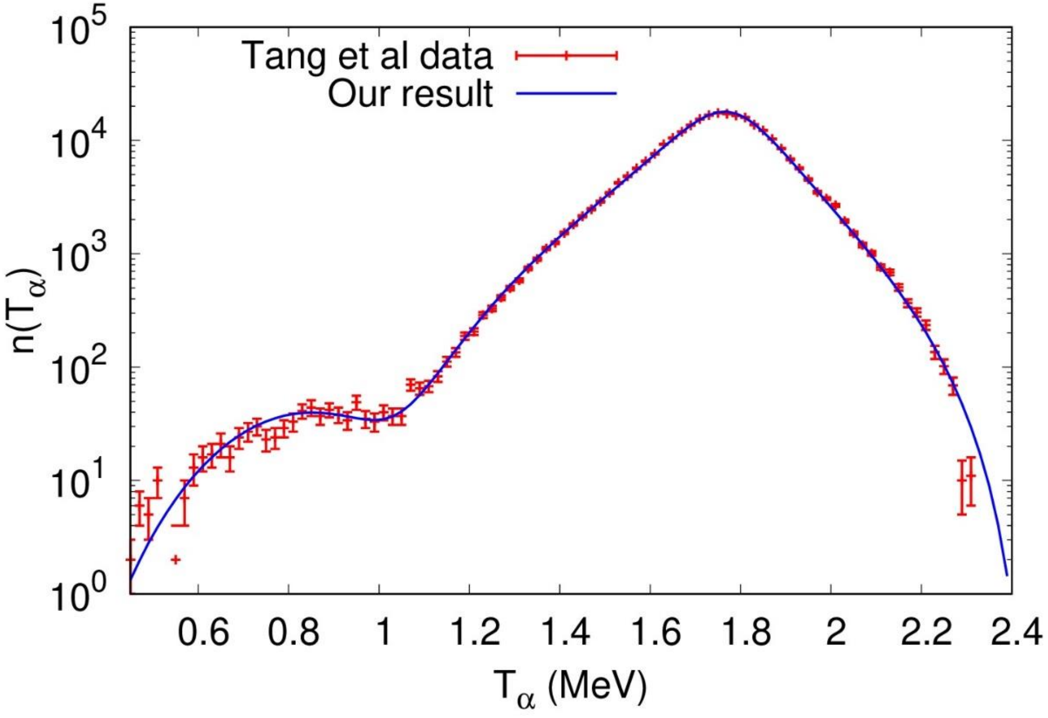
$$K_1(p) = -\frac{1}{a_1} + \frac{1}{2} r_1 p^2 - \frac{1}{4} P_1 p^4 + Q_1 p^6 \,,$$



Numerical results

- Beta delayed alpha energy distributions from nitrogen-16





- Fitted parameters

Exp. data set	Azuma *et al.*	Tang *et al.*
C (MeV^{-6})	$7.2(4) \times 10^{6}$	$4.22(7) \times 10^{6}$
$C_a^{(l=1)}$ (MeV^{-2})	$-6.9(2) \times 10^{-3}$	$-9.46(5) \times 10^{-3}$
$D_a^{(l=1)}$ (MeV^{-2})	$2.61(9)$	$3.36(3)$
$D_b^{(l=1)}$ (MeV)	$-2.55(2) \times 10^{5}$	$-2.297(4) \times 10^{5}$
$C_b^{(l=3)}$ (MeV^{3})	$-2.65(5) \times 10^{-7}$	$-2.46(1) \times 10^{-7}$
χ^2/N (N)	4.06 (91)	3.56 (93)

where $C_b^{(l=1)}$ and $C_b^{(l=3)}$ are fixed by branching ratio of the beta decay.

Discussion

- The cluster EFT reproduces well the data of beta delayed alpha emission from nitrogen-16.
- The ‘’background levels” introduced in R-matrix are now interpreted as a “non-pole contribution.”
- We confirm that the two sets of the experimental data are not consistent with each other. New experiment will be worth doing.

Future plan

- Elastic alpha-carbon-12 scattering for the d-wave channel including two resonant states of oxygen-16 explicitly
- Radiative proton capture on nitrogen-15 for the study of transition between CNO cycle and hot-CNO cycle
- Alpha transfer reaction from initial litium-7 and carbon-12 state to estimate the ANCs for the subthreshold states of oxygen-16