Production and Structure of (*p*-shell) Ξ-Hypernuclei

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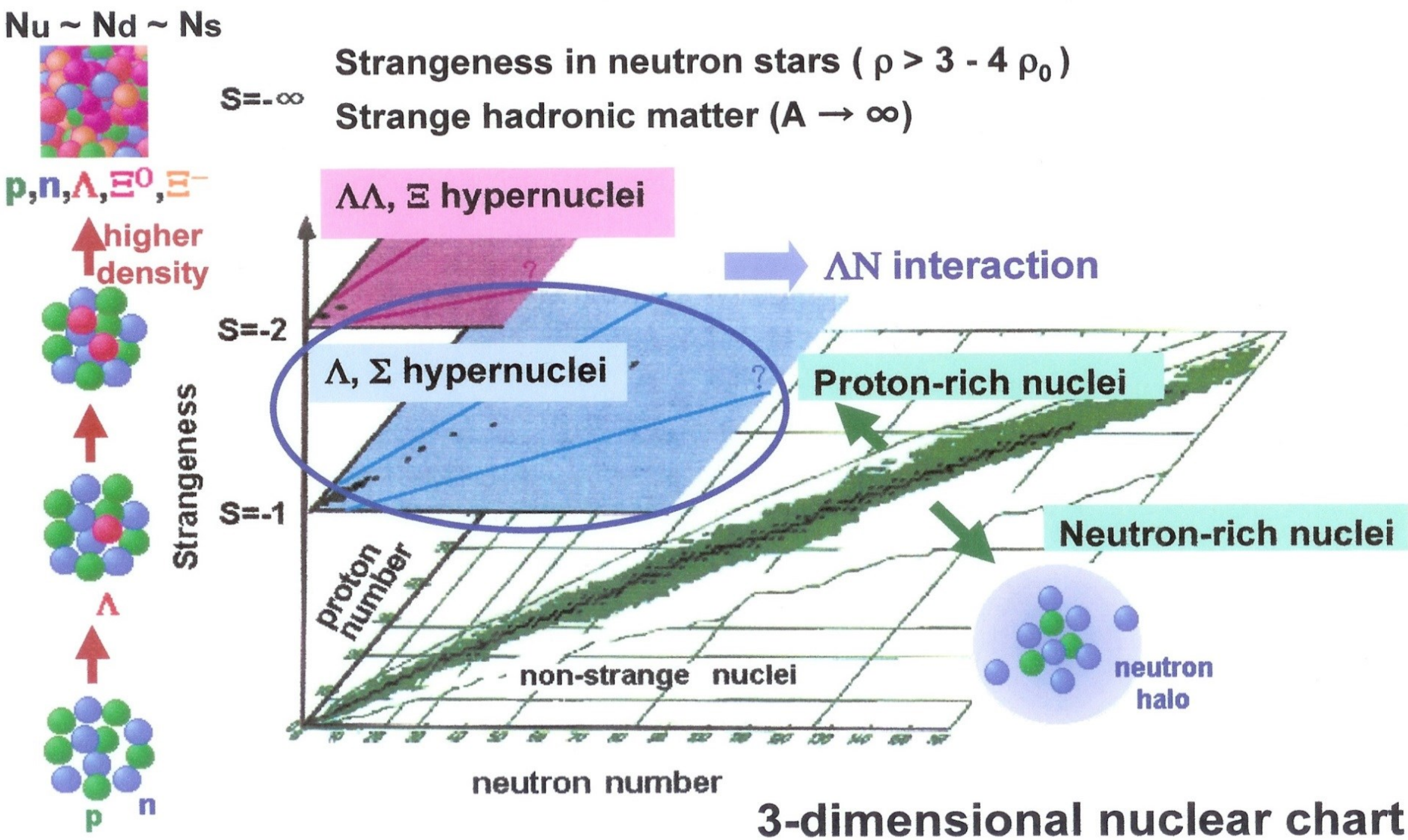
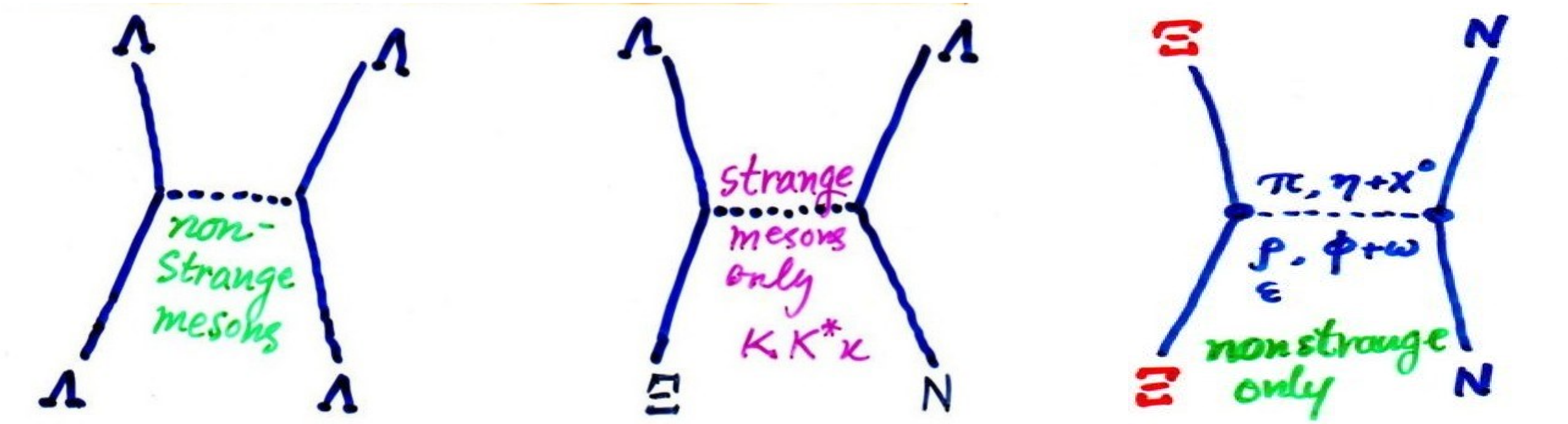
Ξ-Hypernuclei are not well known, but its study is an entrance to the S=−2 world.



(taken from H.Tamura)

Why Ξ-hypernuclei ?

1) They provide unique information on the *S*=-2 B-B interactions inaccessible otherwise.



2) High-priority experiment at J-PARC

E-05: ^{12}C(K-,K+) $_{Ξ}{}^{12}$Be reaction data have appeared

→ Realistic Calculations are required.

CONTENTS

Focus on the theoretical status of Ξ-hypernuclear productions

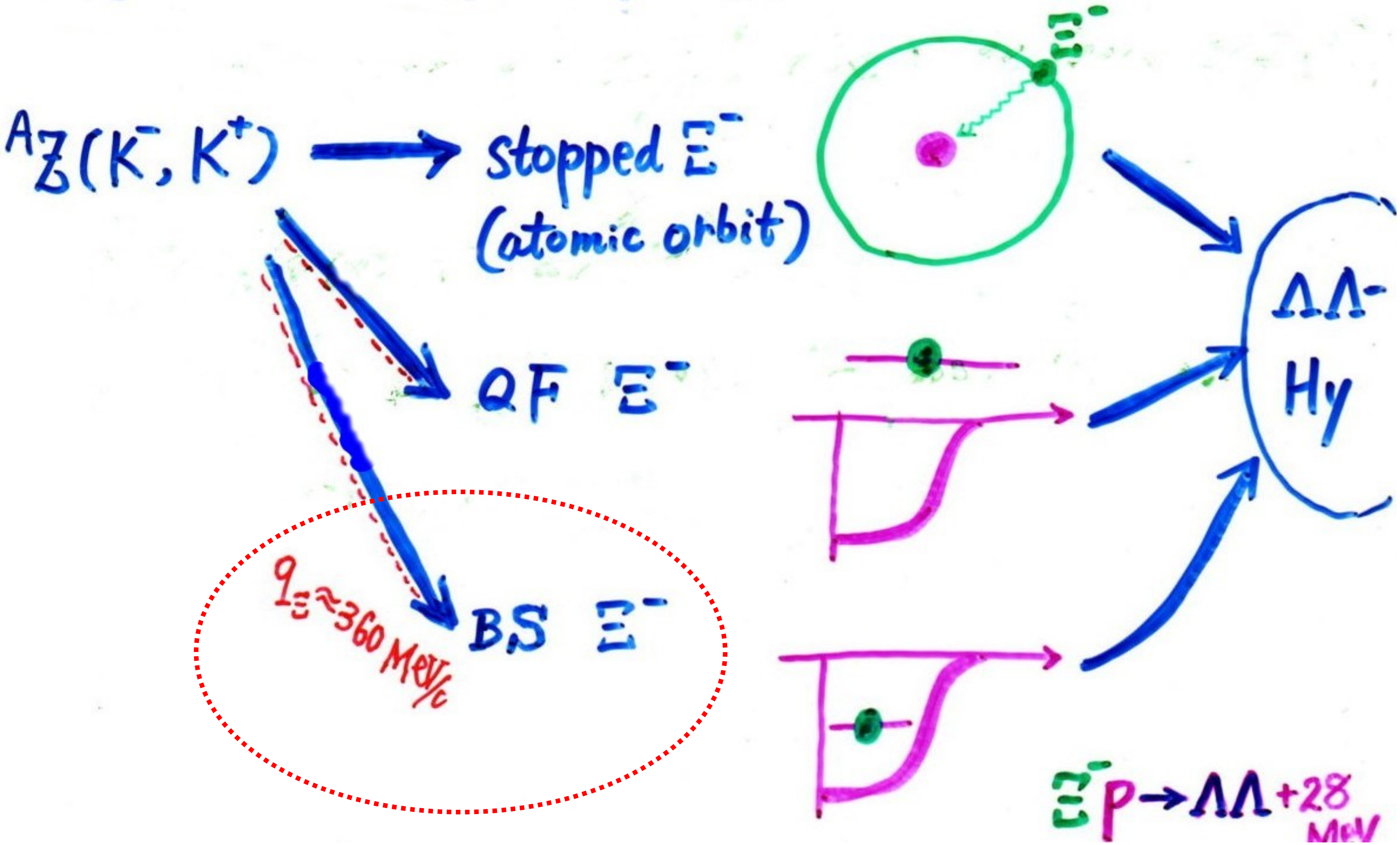
1. DWIA based on the one-body motion of Ξ in an average potential (WS)

2. DWIA with use of many-body Ξ hypernuclear W.F. based on the available Ξ-N interactions

3. Possible few other targets next to ^{12}C

4. Summary

Three cases of Ξ production on **nuclear targets:**



1. DWIA cross sections with Ξ one-body treatment

(1) Ξ one-body motion in an average nuclear potential such as W-S and/or some folding potentials.

(2) Nuclear core-excitations are not taken into account.

(3) K- and K+ distorted waves are obtained by solving the Klein-Gordan Eq. (OR one may take the eikonal approximation.)

DWIA Treatment within Kapur-Peierls method for $^{A}\mathbf{Z}(K^-,K^+)\,^{A}_{\Xi}\mathbf{Z'}$ reaction cross section

$$\frac{d^2\sigma}{d\Omega dE_Y} = \xi \left[\frac{d\sigma(\theta)}{d\Omega} \right]_{\rm elem} S(E_Y, \theta) ,$$

$$S(E_Y, \theta) = -\frac{1}{\pi} \sum_f \mathrm{Im} \left[\frac{N_f(E_Y, \theta)}{E_Y - \epsilon_f(E_Y)} \right] .$$

ξ = kinematical factor for 2-body to A-body frame transformation

$$N_f(E_Y, \theta) = \langle \Phi_0 | \hat{O}^\dagger(\theta) | \Psi_f(E_Y) \rangle \langle \tilde{\Psi}_f(E_Y) | \hat{O}(\theta) | \Phi_0 \rangle .$$

$$\hat{O}^{(K^-,K^+)} = \int d^3\boldsymbol{r}\, \chi^*_{K^+}(\boldsymbol{k}_f, a\boldsymbol{r}) \chi_{K^-}(\boldsymbol{k}_i, \boldsymbol{r}) \sum_{\nu=1}^{A} V_-^{2}(\nu) \delta\left(\boldsymbol{r} - \frac{M_c}{M_A} \boldsymbol{r}_\nu \right) ,$$

$$\chi^*_{K^+}(\boldsymbol{k}_f, a\boldsymbol{r}) \chi_{K^-}(\boldsymbol{k}_i, \boldsymbol{r}) = \sum_{LM} i^L \sqrt{4\pi [L]}\, \tilde{j}_{LM}(k_i, k_f, \theta; a, r) Y_{LM}(\hat{\boldsymbol{r}}) .$$

$\sigma_{K^-p} = 32.5$ mb , $\sigma_{K^-n} = 25.5$ mb , $\sigma_{K^+p} = 19.6$ mb and $\sigma_{K^+n} = 20.1$ mb ,

ε (E)= solutions of the following Hamiltonian, depending on the final hypernuclear excitation energy E(given)

$$\mathcal{H}=(H_N+T_Y+U_Y(r)+\sum v_{YN})+\frac{\hbar^2}{2m_Y}\delta(r-r_c)\left(\frac{d}{dr}-\frac{b}{r_c}\right),$$

$$b=\frac{d\phi_l(k_Y;r)/dr}{\phi_l(k_Y;r)/r}\bigg|_{r=r_c},\quad \phi_l(k_Y;r)\equiv r\{j_l(k_Y r)+in_l(k_Y r)\}.$$

Continuum: Boundary condition for each l at channel radius rc,

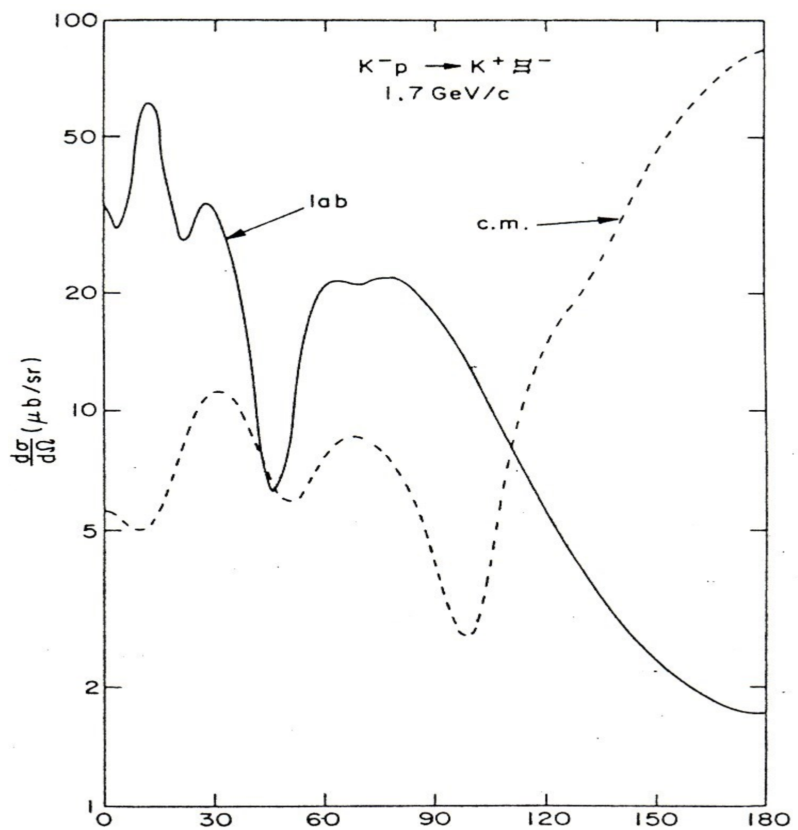
For the case of bound states (E<0), if any, $S(E_Y;\ )$ tends to the effective number Zeff.

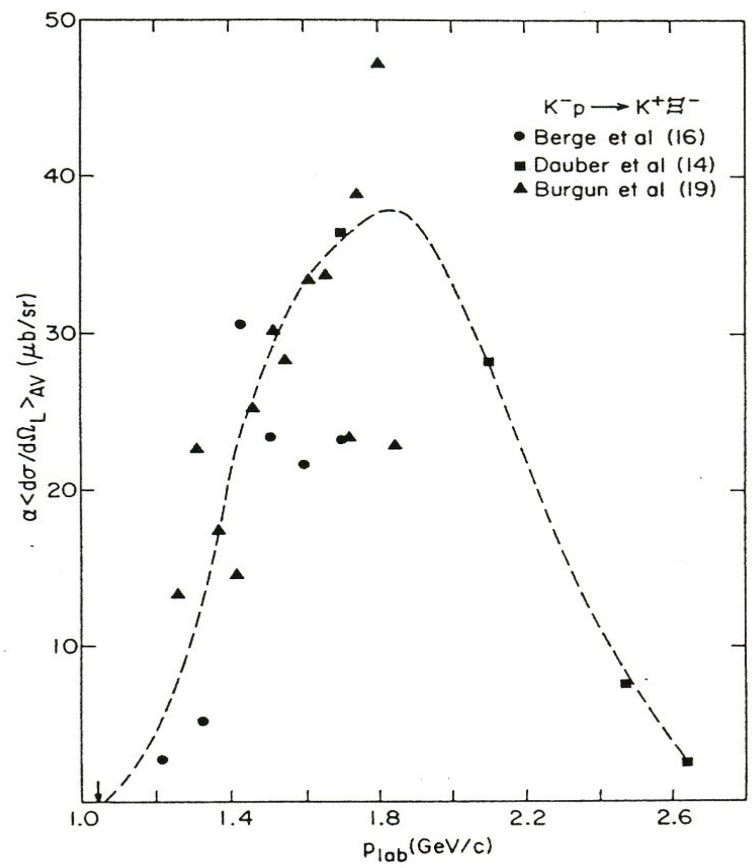
$$\frac{d\sigma(\theta)}{d\Omega_L}=\xi\left[\frac{d\sigma(\theta)}{d\Omega_L}\right]_{K^-p\to\Xi^-K^+}Z_{\rm eff}(i\to f;\theta).$$

Use the empirical Ξ-production cross section, angular distribution and p_K-dependence

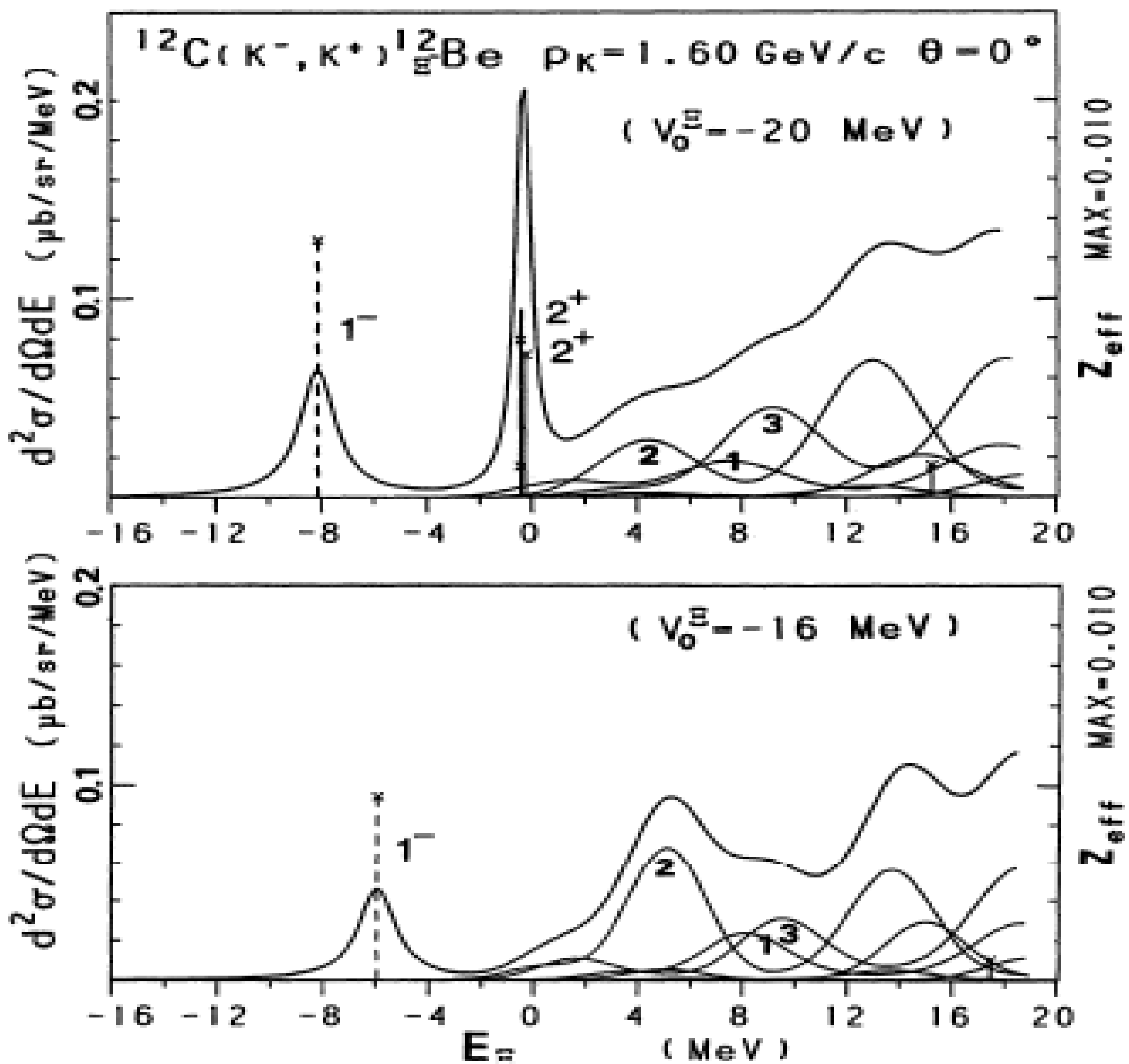
Data from V.Flamino et a, CERN-HERA Report 79-02 (1979)

Pioneering work by C.B.Dover and A.Gal, Annals of Phys. **146** (1983)





One-body potential model naturally leads to the single-hyperon states such as $\mathbf{s}_\Xi$ and $\mathbf{p}_\Xi$, combined with a proton hole



Arbitrary smearing widths are used in these figures

Ξ-N interactions are not taken up to this stage (except W-S pot.)

→**Use basic Xi-N interactions**

Typical meson theoretical models:

Nijmegen model-D, Ehime (Ueda)

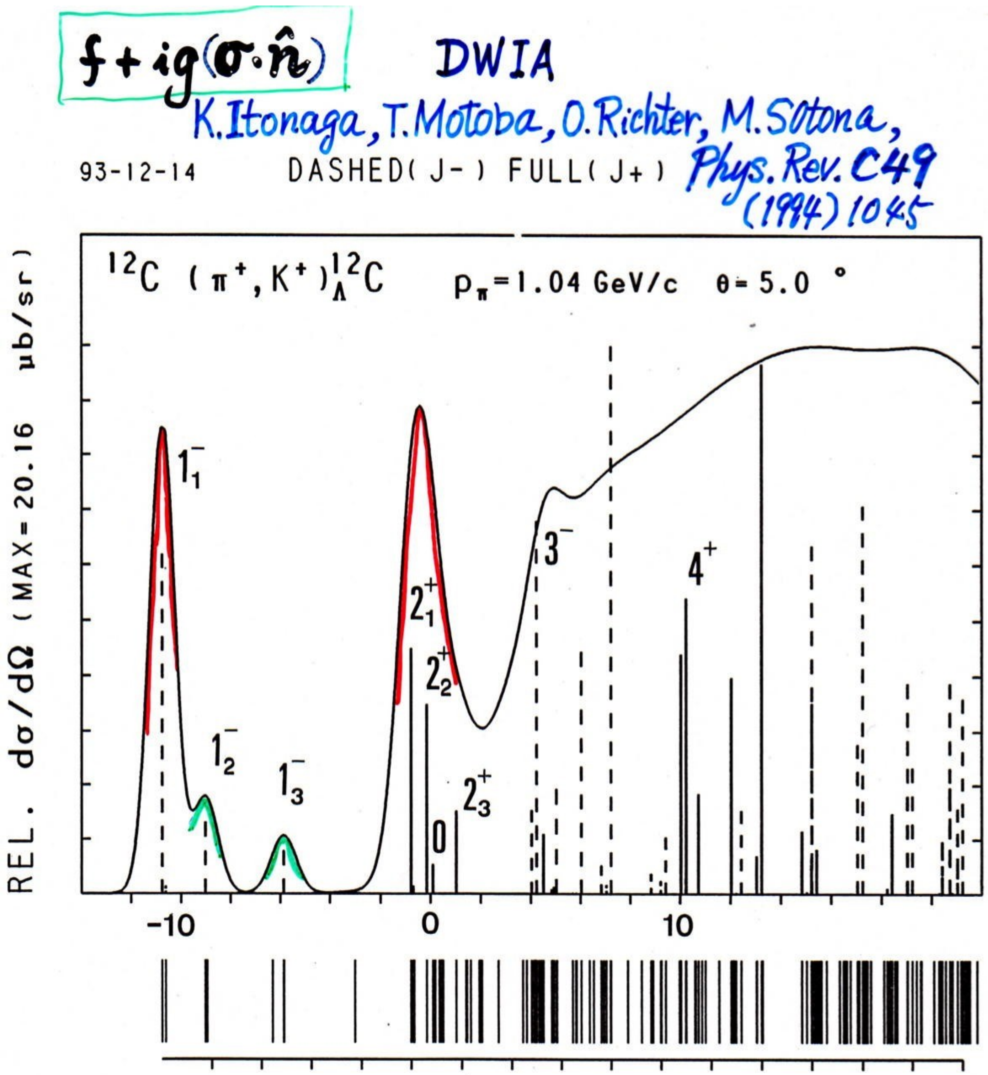
Nijmegen ESC04d, ESC08a, ESC08c, ESC2016

(Gmatrix: 2 or 3-range Gaussian expressions, YNG)

→dynamical nuclear core excitations are taken into account ($^{11}B^{*} + \Xi^{-}$),

This theory works quite nice as proved in (π+,K+).

CAL (Itonaga et al 1994) vs. EXP (Hotchi et al, 2001)



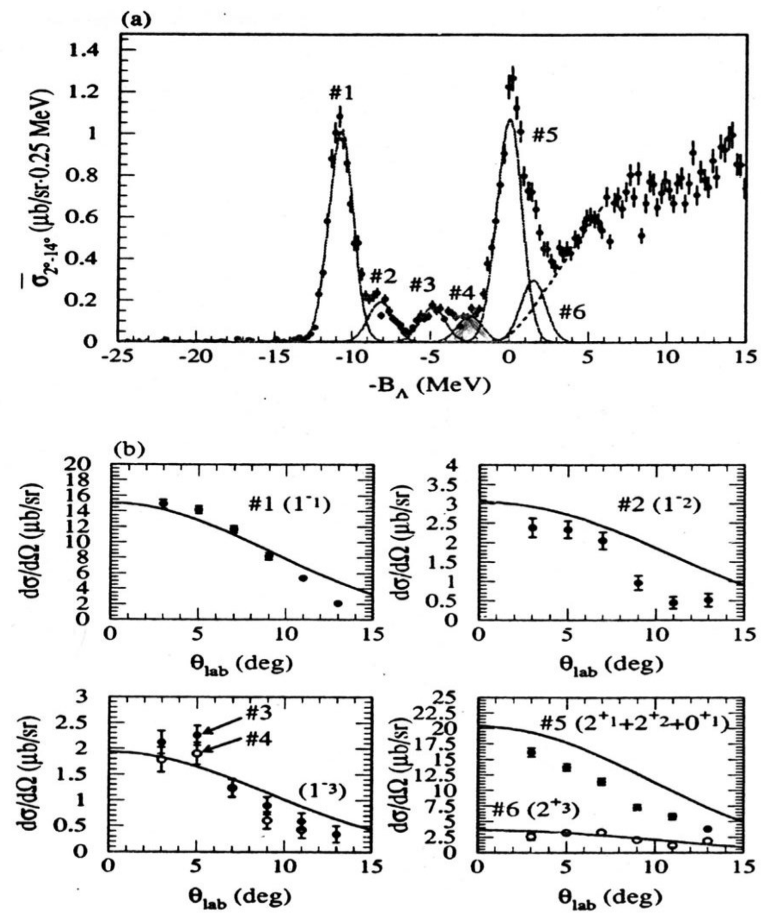


FIG. 8. (a) $^{12}_{\Lambda}$C spectrum obtained with the thick carbon target. (b) Angular distributions of kaons leading to the observed peaks for the ^{12}C(π^+,K^+) reaction derived from the above high-statistics

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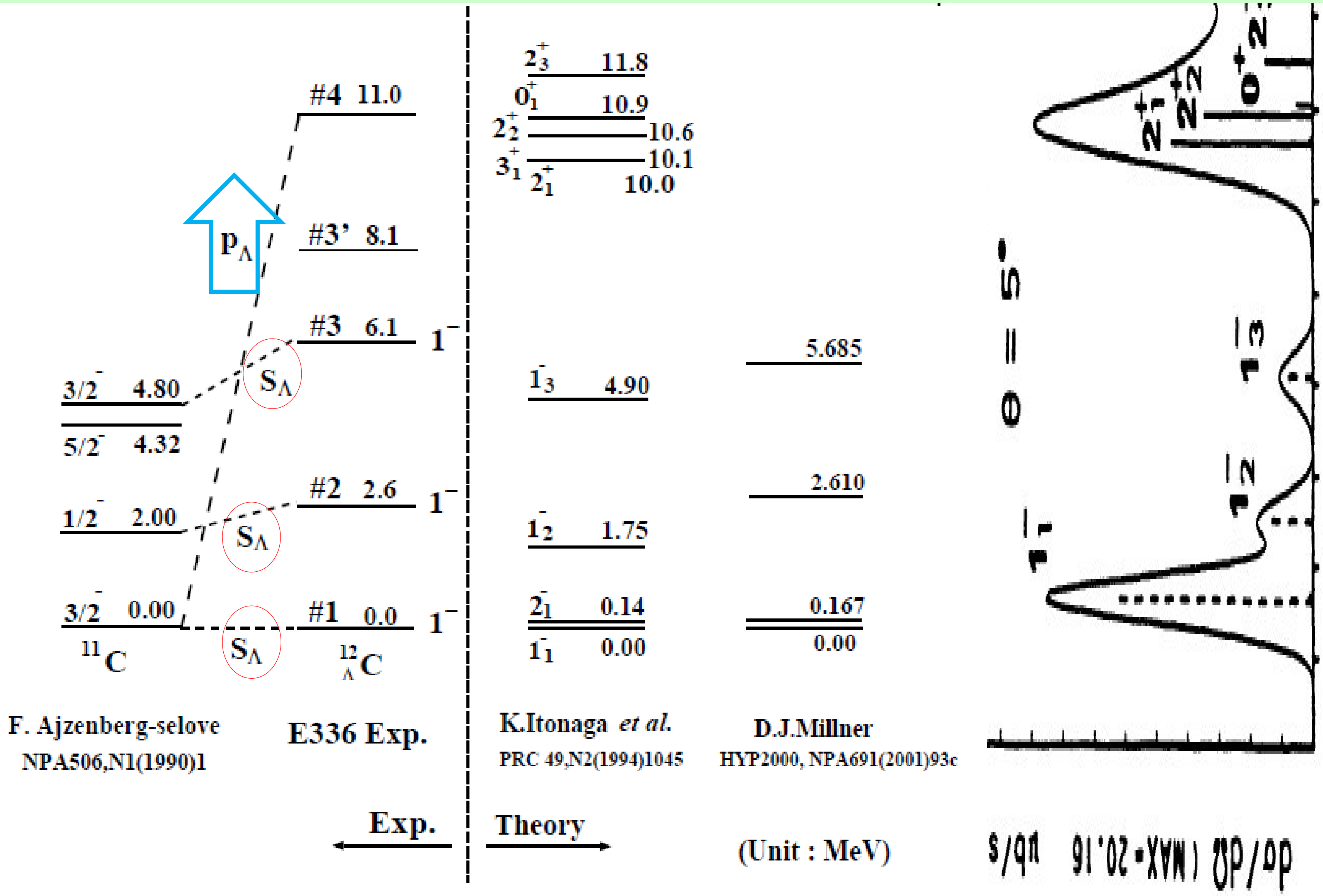
Hypernuclear low-lying states are composed of the coupling between s-state L with the 11C excited states.



2. Many-body calculations

Take account of :

1) dynamical nuclear core excitations ($^{11}B^{*}+\Xi^{-}$), V(NN)=conventional

2) NN and ΞN effective interactions on equal footing,

3) hyperon tail (radial) behavior of $\phi_{\Xi}(r)$ carefully: 0s+1s+2s, 0p+1p+2p, ….

- $H_{total} = H^{(Cohen\text{-}Kurath)} + t_Y + \sum \boldsymbol{V}^{(YNG)}$

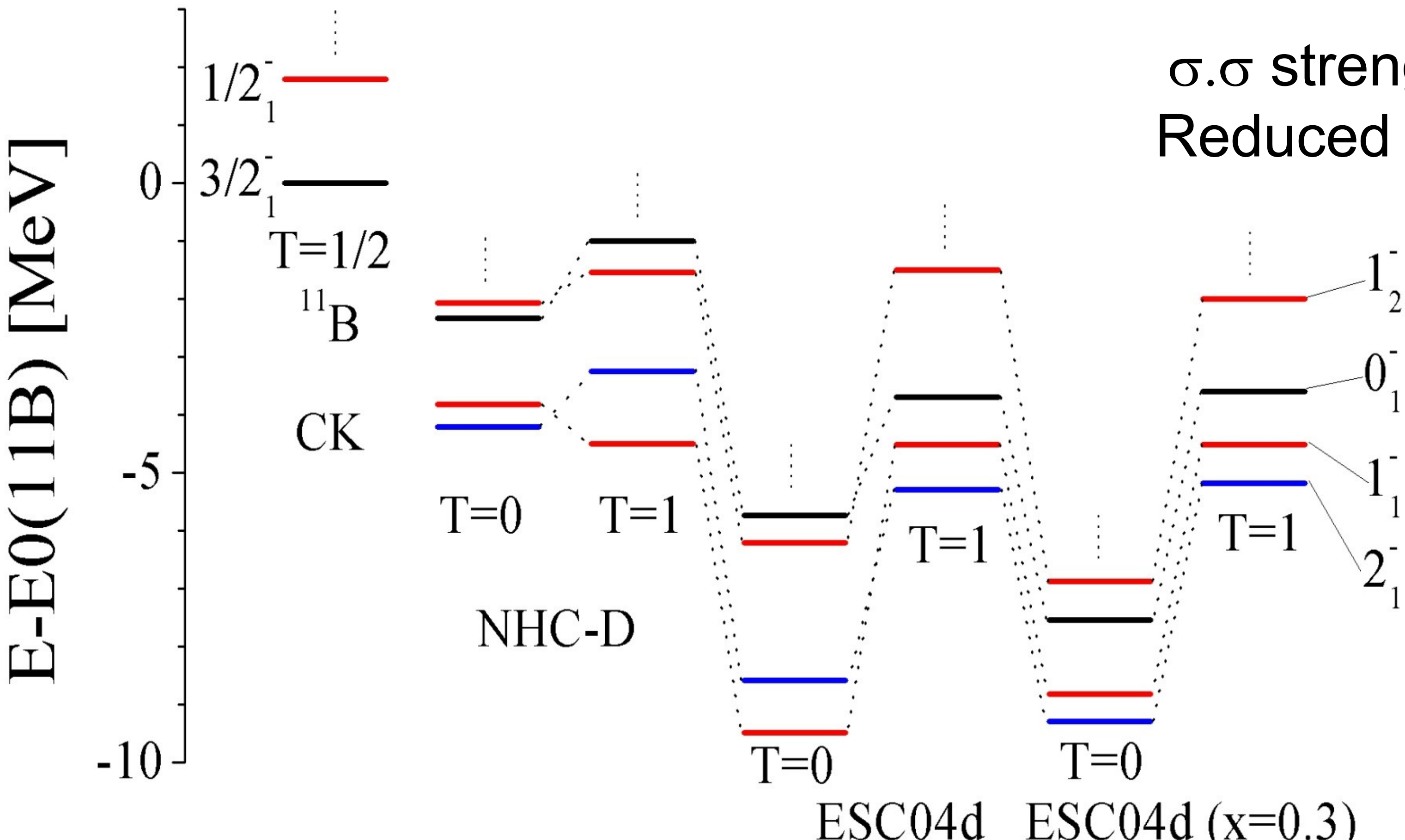
- Interaction property is essential to form the XS spectrum

$\boldsymbol{V}^{(YNG)}$: NHC-D, Ehime, ESC04d, ESC08, ESC08c, ESC2016

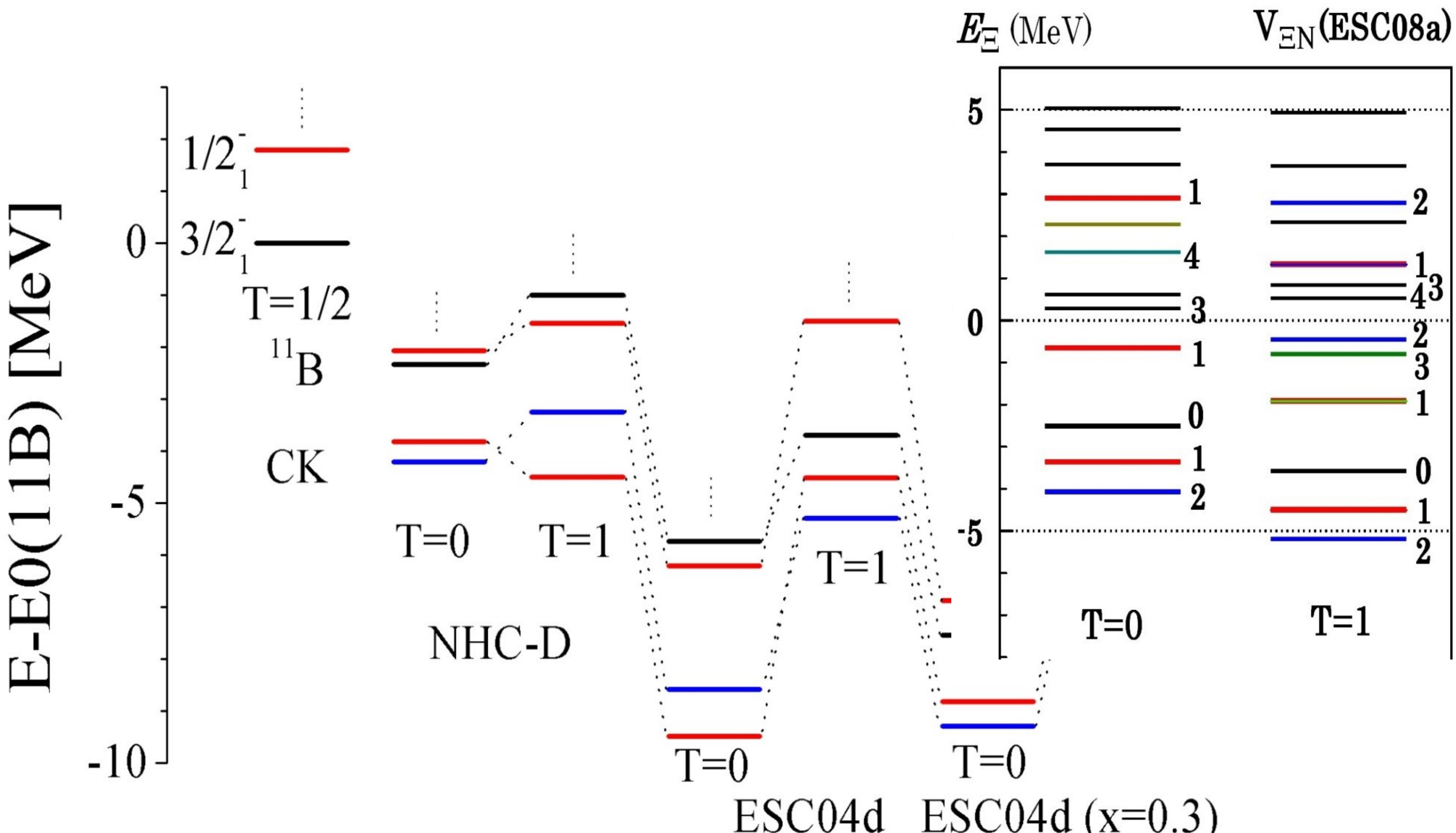
Show how different they are:

NHC-D: T=0 & 1 states appear in the similar E region.

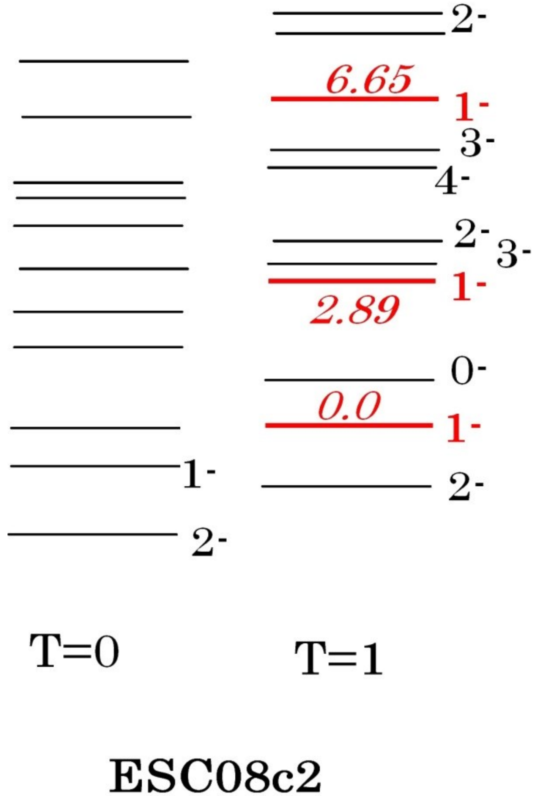
ESC04d: deep T=0 states.



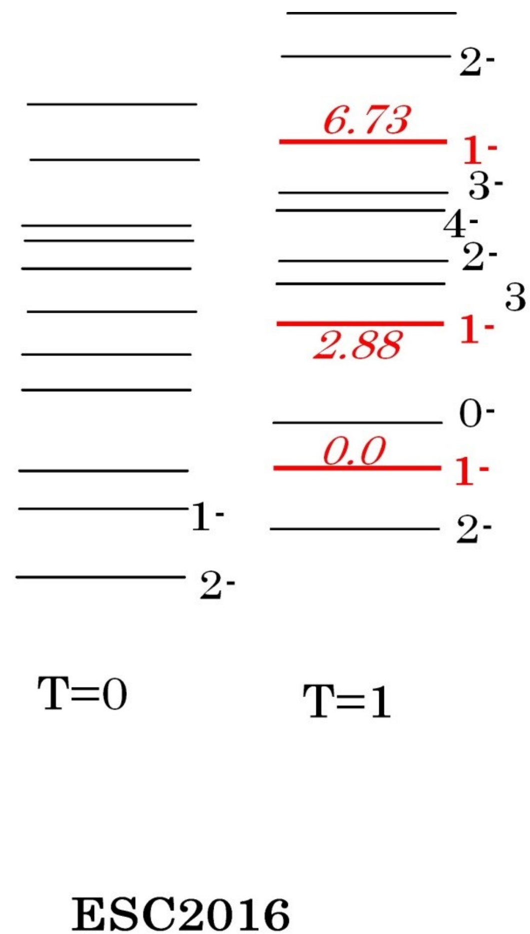
ESC04d: T=0 states are deep,
ND, ESC08: T=0 & 1 states appear in the similar energy region. T=1 is a little deeper.



Most recent versions of ESC08 model do not lead to big change in *relative level structure concerned in (K-,K+) reaction*



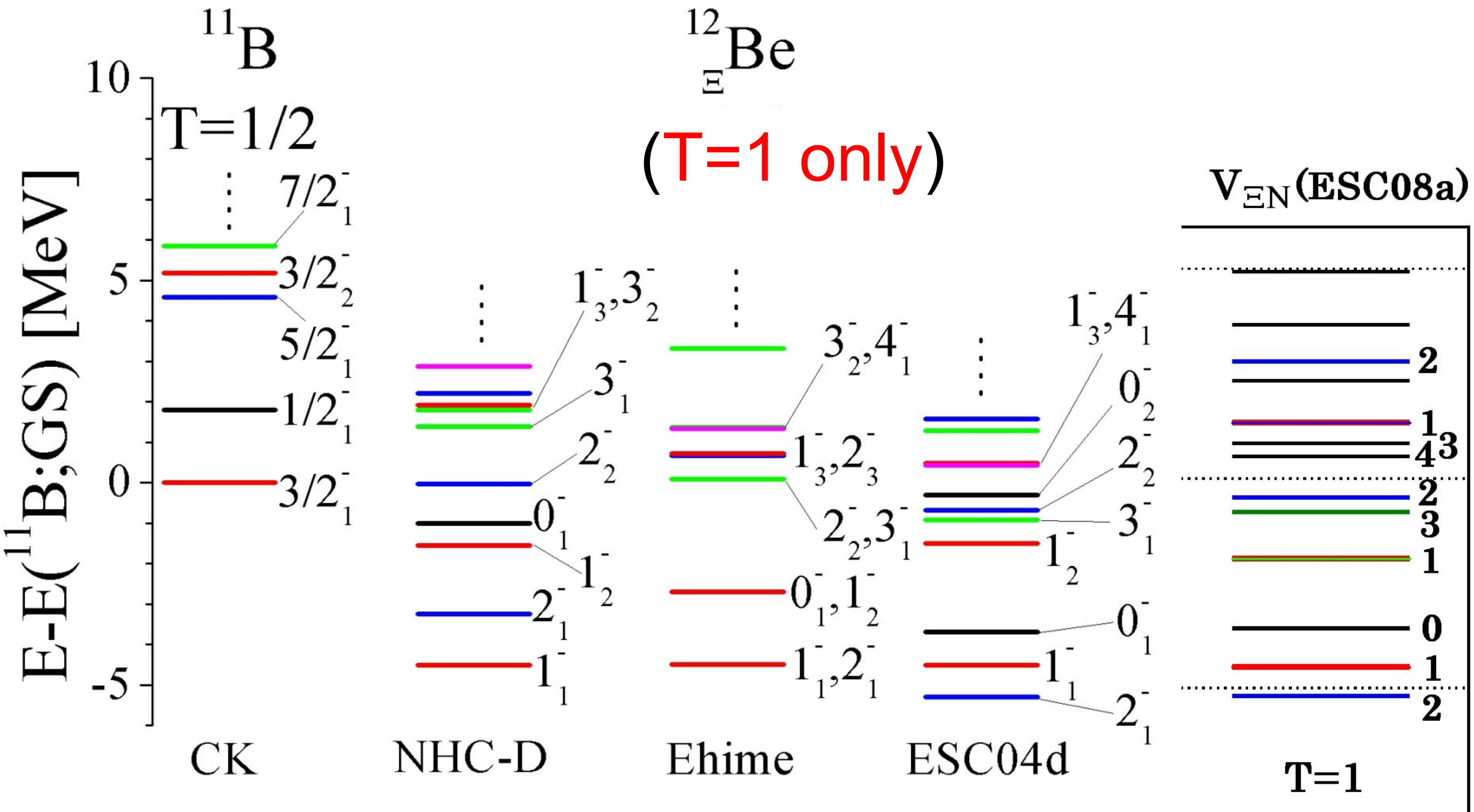
ESC08c1



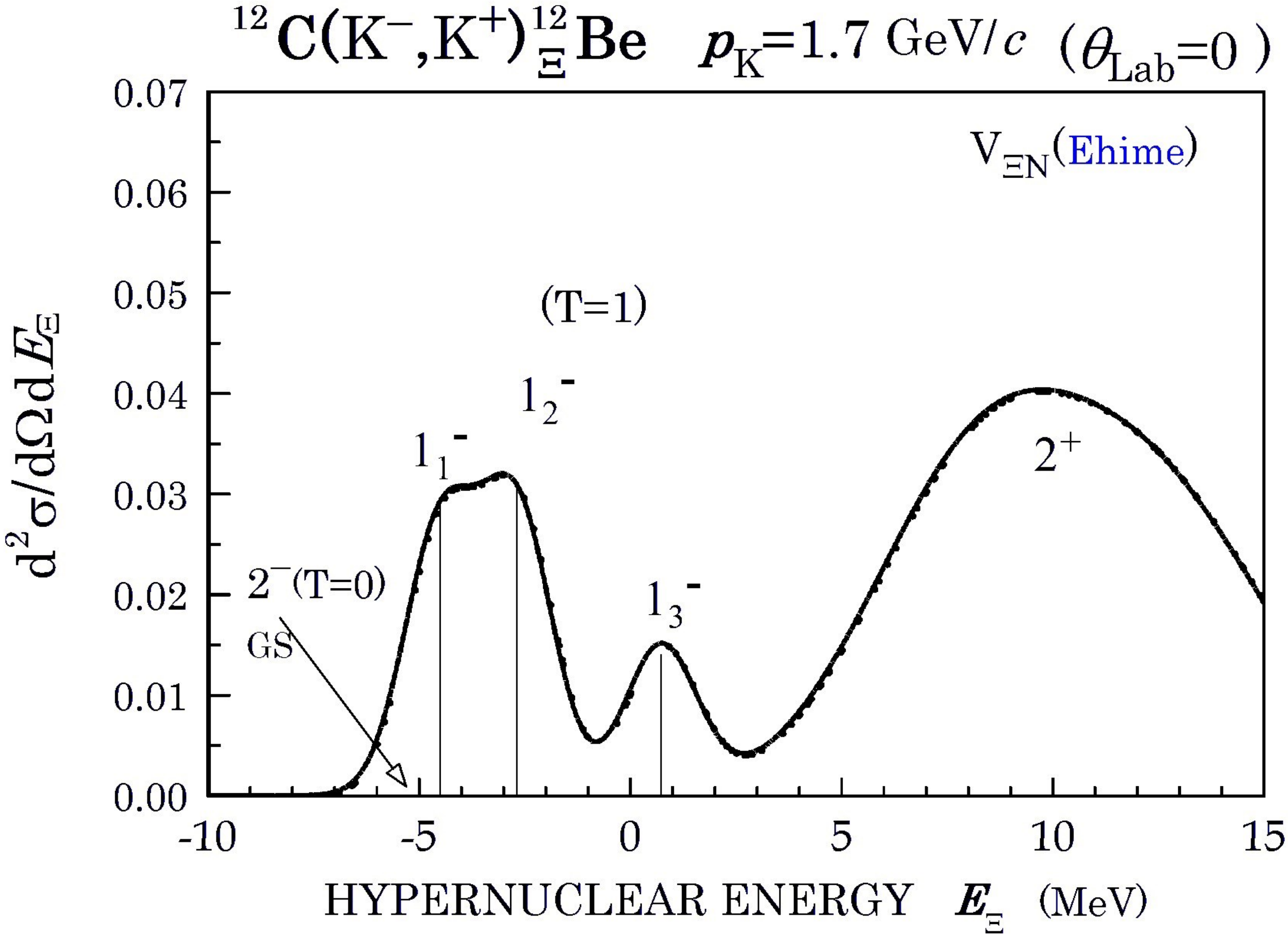
ESC16MPP

Reference position of J=1-(T=1) states.

The relative positions of J_n show the different σ.σ interaction nature of $V_{\Xi N}$.

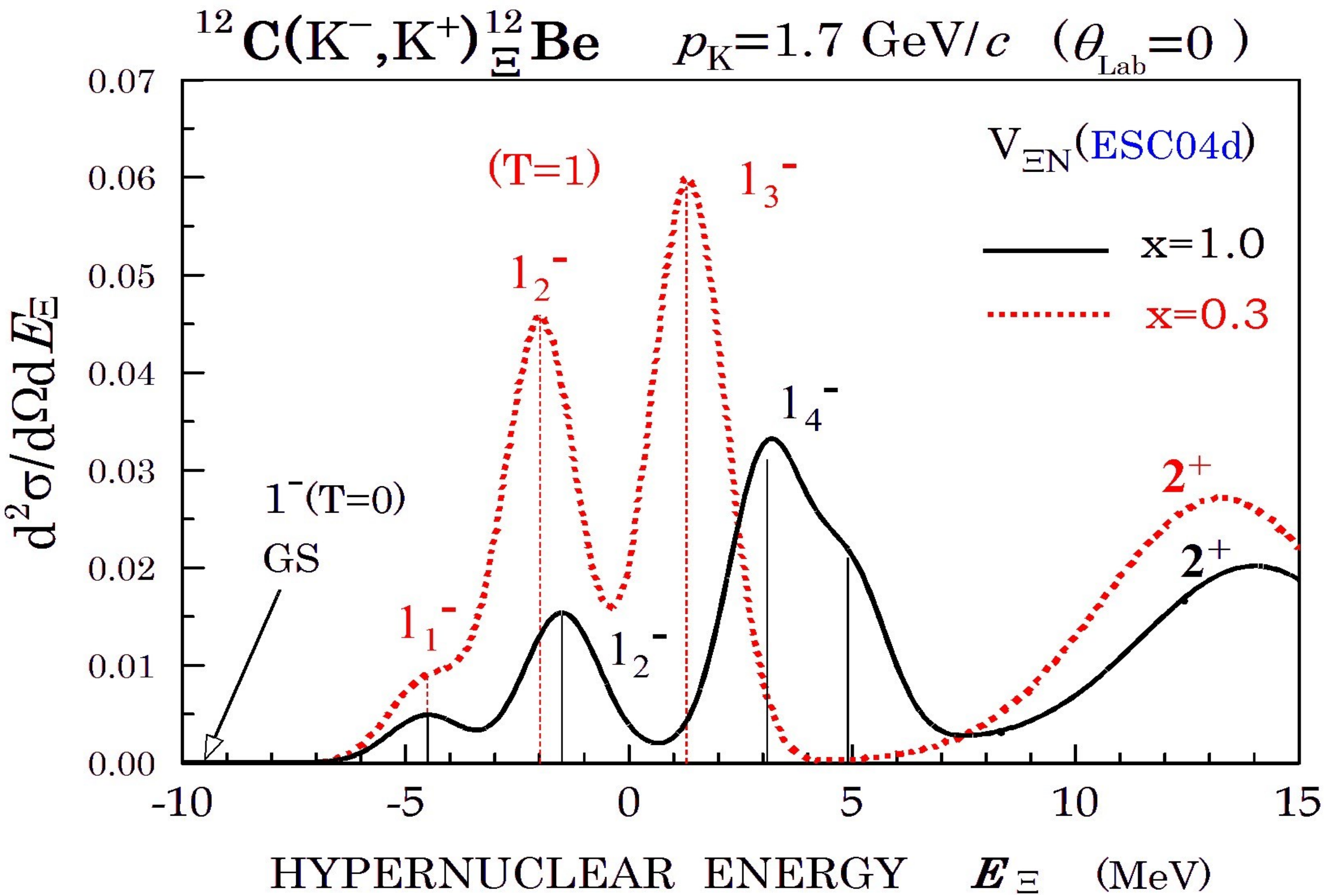


Spectrum (1): Ehime case.



Spectrum (2): ESC04d case

(large S- & T-dependence)



Why so sensitive V(Xi-N)-dependence

(1) Nijmegen NHC-D vs. ESC04d

- **Different partial-wave contributions**
  NHC-D (large p-state attraction) vs. ESC04d(s-state)
- **ESC04d (quite large spin- & isospin-dependence)**

Table 1: Ξ single particle energies U_Ξ and conversion widths Γ_Ξ at normal density calculated with ESC04d and NHC-D. S-state contributions in $(TSLJ)$ states and total P-state contributions are also given. All entries are in MeV.

	$^{11}S_0$	$^{13}S_1$	$^{31}S_0$	$^{33}S_1$	P	U_Ξ	Γ_Ξ
ESC04d($\alpha = 0$)	6.4	[illegible]	6.4	−5.0	−6.9	−18.7	11.4
ESC04d($\alpha = .18$)	6.3	[illegible]	7.2	−1.7	−5.6	−12.1	12.7
NHC-D	−2.6	0.7	−2.3	−0.4	[illegible]	−21.4	1.1

(From Y. Yamamoto)

(2) Core-Ξ coupling: ESC04d vs. ND

The spatial symmetry of target GS does not persist due to large spin-dep., when a proton is replaced by Ξ.

Mixing probability in $^{12}_{\Xi}Be$

ESC04d		Jπ of the core (^{11}B)		
T=1 Jπ	BE(Ξ)	3/2- 1st (GS)	1/2- 1st (1.8MeV)	3/2- 2nd (5.2MeV)
1st 1-	4.5MeV	58.5%	39.0%	1%
2nd 1-	1.5MeV	13.3%	34.0%	48.7%

NHC-D		Jπ of the core (^{11}B)		
T=1 Jπ	BE(Ξ)	3/2- 1st (GS)	1/2- 1st (1.8MeV)	3/2- 2nd (5.2MeV)
1st 1-	4.5MeV	85.5%	12.3%	2%
2nd 1-	3.0MeV	13.1%	85.8%	1%

- Probability for $0s_{1/2}(\Xi) \otimes J^{\pi}(\mathrm{Core})$
- ESC04d induce large mixing.
- It probably reflects on the spectra of (K^{+},K^{-}) reaction.

Trying to use the most recent Ξ-N interaction from Nijmegen (ESC08)

Table 1: Partial wave contributions to $U_\Xi(\rho_0)$

model	T	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	U_Ξ	Γ_Ξ
ESC08	0	4.0	−2.7	0.2	−2.2	0.6	−1.1		
	1	7.0	−19.5	−0.3	0.1	−3.6	−0.7	−18.0	6.0
ESC04d	0	6.4	−19.6	1.1	1.2	−1.3	−2.0		
	1	6.4	−5.0	−1.0	−0.6	−1.4	−2.8	−18.7	11.4

V(Ξ-N).

Both come from strong S-T-dependence

Table 2: $U_\Xi(\rho_0)$ and partial wave contributions for ESC08c, ESC08c$_1^+$ and ESC08c$_2^+$ calculated with the CON choice. Γ^c_Ξ denotes ΞN-$\Lambda\Lambda$ conversion width. All entries are in MeV.

	T	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	U_Ξ	Γ^c_Ξ
ESC08c	0	1.1	−6.9	−0.2	1.6	1.5	−1.8		
	1	9.0	−16.9	1.2	0.8	−2.3	0.3	−12.6	7.0
ESC08c$_1^+$	0	2.0	−5.5	−0.1	1.5	1.6	−1.5		
	1	9.8	−13.5	1.6	0.9	−1.9	0.9	−4.2	6.9
ESC08c$_2^+$	0	1.7	−5.9	−0.1	1.6	1.6	−1.5		
	1	9.3	−14.6	1.6	0.9	−1.9	0.9	−6.4	6.6

	T	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	U_Ξ	Γ^c_Ξ
ESC2016	0	1.7	−7.6	−0.2	0.5	1.5	−1.9		
	1	9.1	−9.8	1.2	0.8	−2.2	0.3	−6.6	6.7
ESC2016	0	2.5	−5.8	−0.1	1.2	1.6	−1.6		
+MPP	1	9.7	−6.9	1.6	0.9	−1.8	0.9	+2.3	6.6

Partial wave contributions (from Y.Yamamoto)

Ξ-N interactions used in Shell Model

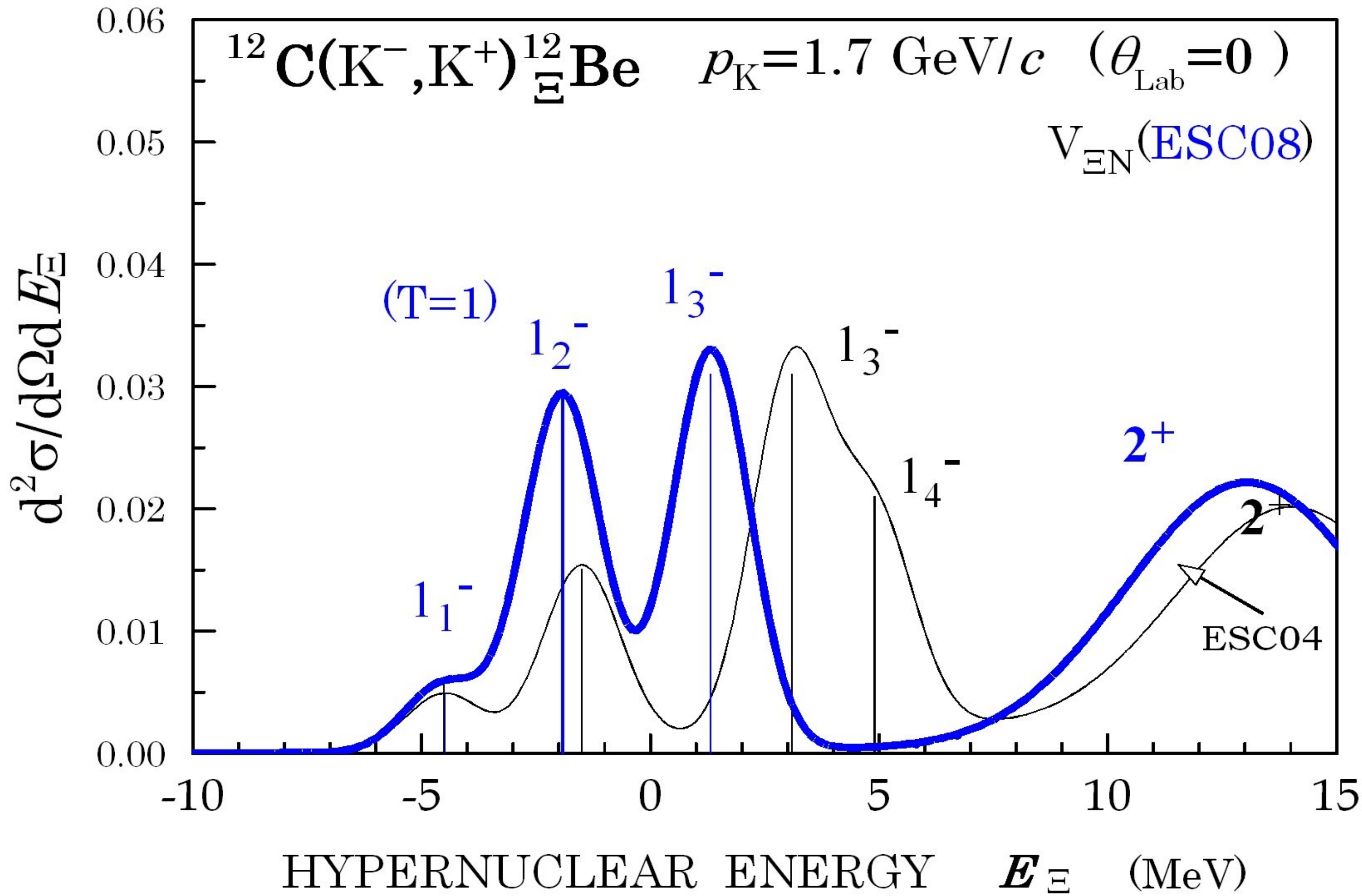
Comparison in the form of $V = -V_0 + \Delta(\sigma.\sigma)$

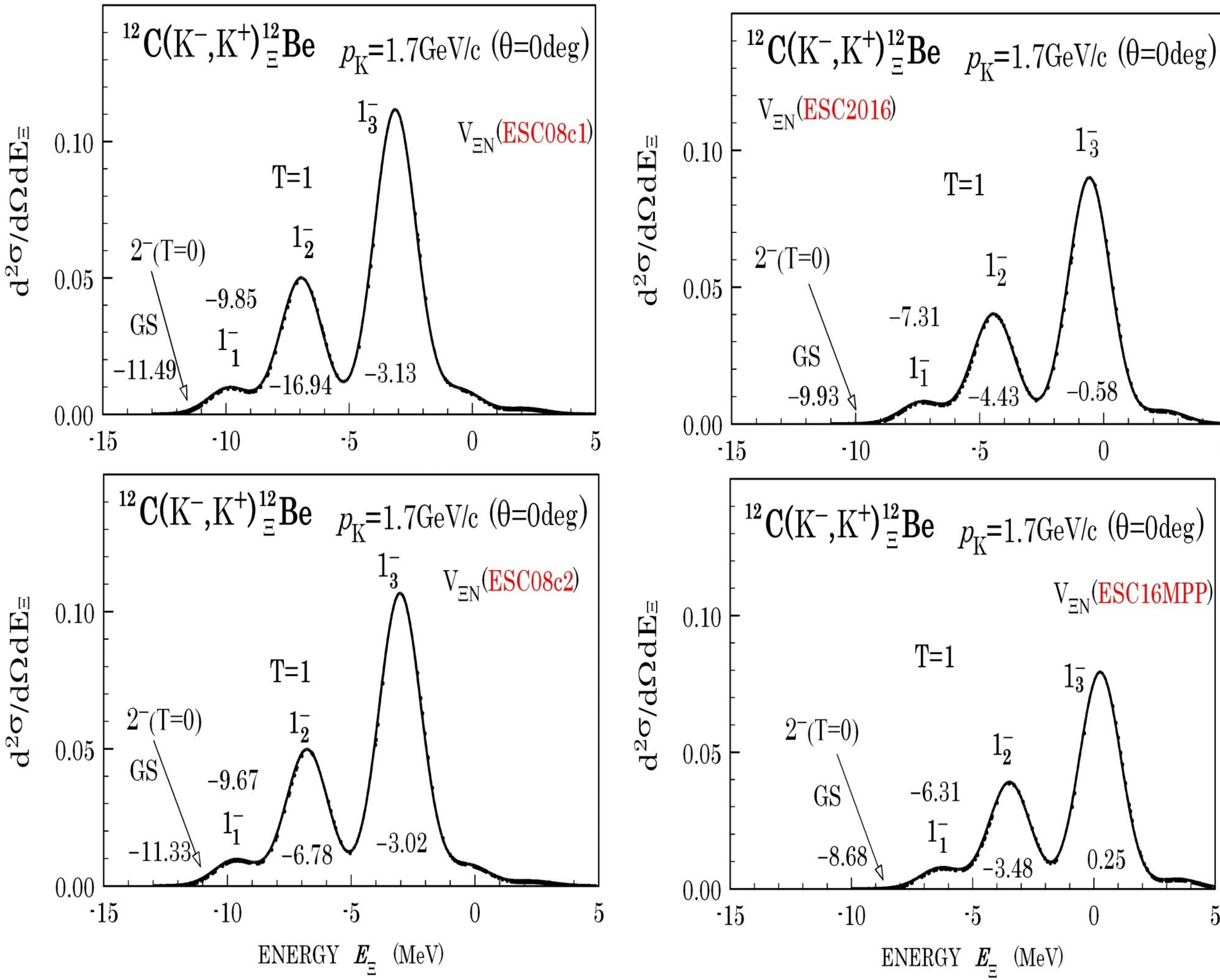
		V_0	Δ	Δ/V_0
NΞ(ESC04d)	T=0	4.98	-15.81	-3.18
	T=1	0.30	-2.96	-9.88
NΞ(NHC-D)	T=0	2.14	4.75	2.23
	T=1	1.55	0.79	0.51
NΛ(NSC97f)	T=1/2	1.36	1.16	0.86
NΛ (Millener)		1.49	0.50	0.33

$\sigma.\sigma$ strengths are quite different beteen ESC and ND, so further trials and improvements are required.

ESC04 modified to be ESC08 !

(continuum bump should be larger)





$^{12}C(K^-,K^+)^{12}_{\Xi}Be$ p_K=1.7GeV/c (θ=0deg)
$V_{\Xi N}$(ESC08c1)
T=1
1_3^-
1_2^-
2^-(T=0)
GS
−11.49
−9.85
1_1^-
−16.94
−3.13
$^{12}C(K^-,K^+)^{12}_{\Xi}Be$ p_K=1.7GeV/c (θ=0deg)
$V_{\Xi N}$(ESC2016)
T=1
1_3^-
1_2^-
2^-(T=0)
GS
−9.93
−7.31
1_1^-
−4.43
−0.58
$^{12}C(K^-,K^+)^{12}_{\Xi}Be$ p_K=1.7GeV/c (θ=0deg)
$V_{\Xi N}$(ESC08c2)
T=1
1_3^-
1_2^-
2^-(T=0)
GS
−11.33
−9.67
1_1^-
−6.78
−3.02
$^{12}C(K^-,K^+)^{12}_{\Xi}Be$ p_K=1.7GeV/c (θ=0deg)
$V_{\Xi N}$(ESC16MPP)
T=1
1_3^-
1_2^-
2^-(T=0)
GS
−8.68
−6.31
1_1^-
−3.48
0.25
$d^2\sigma/d\Omega dE_\Xi$
0.00
0.05
0.10
-15
-10
-5
0
5
ENERGY E_Ξ (MeV)

- The patterns of (K-,K+) spectrum --- “two peak structure” ----- obtained from the most recent versions (ESC08c1, ESC08c2, ESC2016 and ESC16MPP) are not much different from each other. (Ξ in ***s***-state)
- Relative strength of these peaks might change depending on the spin-isospin properties of the Xi-N interactions.

←------→ waiting for the analysis of E05 exp.

Summary

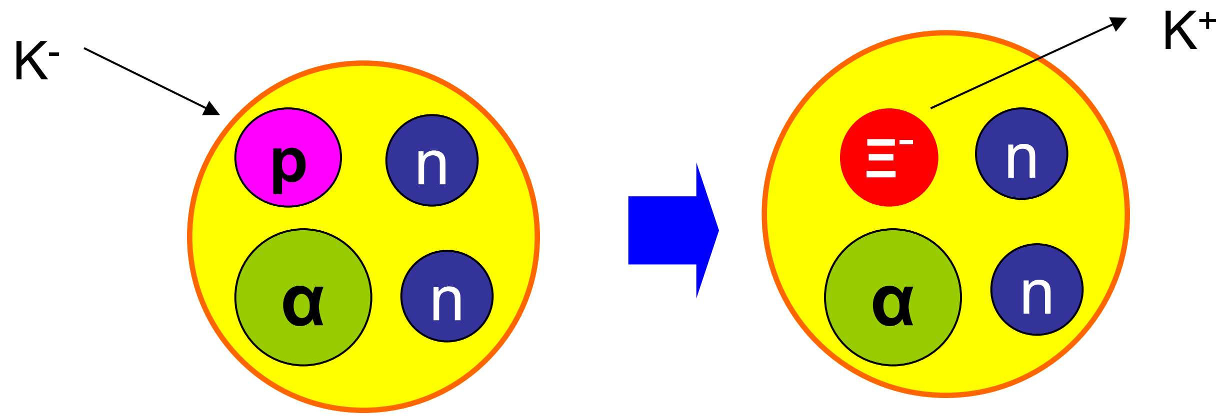
1. Shell-Model many-body WF have been applied to $^{12}C(K^-,K^+)_{\Xi}{}^{12}B$ in DWIA. + ^{10}B

2. Low-lying levels and the reaction strength functions are shown to be quite sensitive to the choice of available Ξ-N interactions.

3. Analyses are in progress, especially, to clarify the effect of Ξ-N spin-dependence on the reaction spectrum so as to improve it.

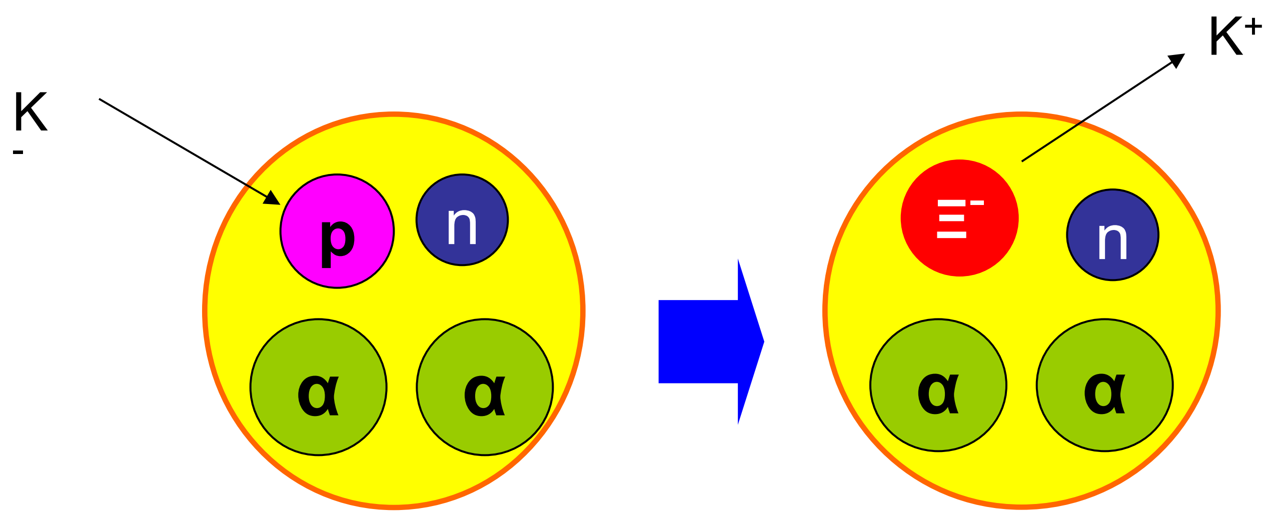
4. It is interesting if the recent E05 experiment surely provides us with good restriction of discriminating the existing Ξ-N interactions.

As the second best candidates to extract information about the spin-, isospin-independent term V_0, we propose to perform…



^{7}Li (T=1/2) $\quad$ $^{7}_{\Xi^-}$H (T=3/2)

Why they are suited for investigating V_0?



^{10}B (T=0) $\quad$ $^{10}_{\Xi^-}$Li (T=1)

Almost spin-saturated case

(Pictures by Hiyama)

$^{10}\mathbf{B}[3^+]$ (K^-,K^+) $^{10}_{\Xi}\mathbf{Li}$ [$^9Be+\Xi^-$]

The lowest J=2- state gets the largest cross section.(ΔL=1-)