EFB22, Krakow, Sep.12, 2012

Analyses of excited states in ^{4}He by complex scaling method

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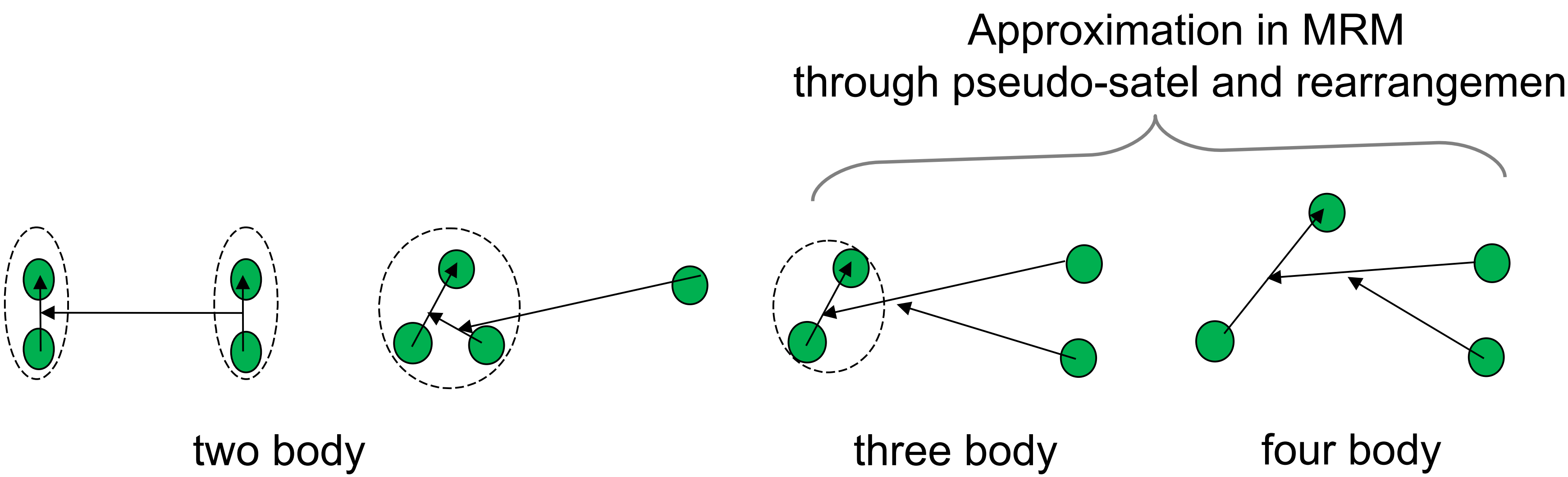
<u>Corrlated Gaussian + Microscopic R-matrix Method</u>

S. Aoyama, K. Arai, Y. Suzuki, P. Descouvemont and D. Baye, FBS52, (2012)97.

K. Arai, S. Aoyama, Y. Suzuki, P. Descouvemont and D. Baye, PRL107 (2011) 132502.

Purpose

We want to solve 4, 5, 6- nucleons reaction in *ab-initio* way by using a correlated Gaussian method with Microscopic R-matrix Method (MRM) and/or Complex Scaling Method(CSM).



In CSM, we can treat them in the same footing.

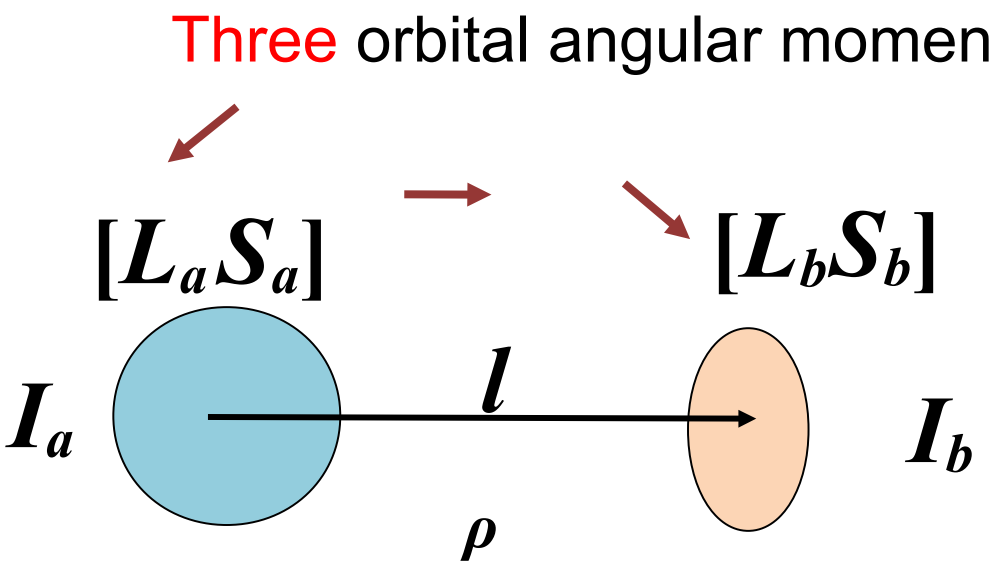
Correlate Gaussian Method

(Single) global vector representation (GVR)

K. Varga, Y. Suzuki, and J. Usukura, FBS24(1998)81

Triple global vector representation (TGVR)

S. Aoyama, K. Arai, Y. Suzuki, P. Descouvemont and D. Baye, FBS52(2012)97



Example
t+d

Correlated Gaussian function with triple global vectors for four nucleon system

Unnatural parity 0^-

L1=L2=L12=L3=1

$$F_{L_1L_2(L_{12})L_3LM}(u_1,u_2,u_3,A,x)$$

$$=\exp\left(-\frac{1}{2}\tilde{x}Ax\right)[[\mathcal{Y}_{L_1}(\widetilde{u_1}x)\mathcal{Y}_{L_2}(\widetilde{u_2}x)]_{L_{12}}\mathcal{Y}_{L_3}(\widetilde{u_3}x)]_{LM}$$

SVM wave function

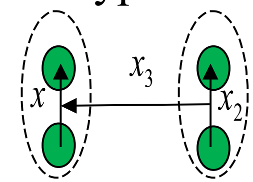
triple global vector

$$\mathcal{Y}_{L_iM_i}(\tilde{u}_ix)=|\tilde{u}_ix|^{L_i}Y_{L_iM_i}(\widehat{\tilde{u}_ix}) \qquad \tilde{u}_ix=\sum_{j=1}^{N-1}(u_i)_jx_j$$

For H-type, we can choose, $\widetilde{u_1}=(1,0,0)$, $\widetilde{u_2}=(0,1,0)$ and $\widetilde{u_3}=(0,0,1)$

We also write the K-type basis function in the same form.

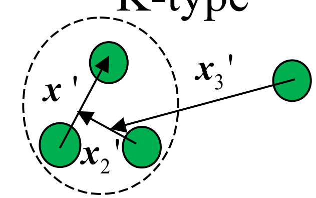
H-type



$$\exp\left(-\frac{1}{2}\widetilde{x'}A_Kx'\right)[[\mathcal{Y}_{L_1}(x'_1)\mathcal{Y}_{L_2}(x'_2)]_{L_{12}}\mathcal{Y}_{L_3}(x'_3)]_{LM}$$

$$x'=U_{KH}x \qquad \widetilde{u_1}=(1,0,0),\ \widetilde{u_2}=(0,-\tfrac{1}{2},1) \text{ and } \widetilde{u_3}=(0,\tfrac{2}{3},\tfrac{2}{3})$$

K-type



$$A=(u_1u_2u_3)A_K\begin{pmatrix}\widetilde{u_1}\\ \widetilde{u_2}\\ \widetilde{u_3}\end{pmatrix}=\widetilde{U_{KH}}A_KU_{KH}$$

Hamiltonian(4-body case)

$$H = \sum_{i=1}^{4} T_i - T_{\rm cm} + \sum_{i<j}^{4} V_{ij} + \sum_{i<j<k}^{4} V_{ijk},$$

Realistic Interaction: AV8’ (+Coulomb+3NF)

V_{ij}: Central+LS+Tensor+Coulomb

Pudliner, Pandharipande, Carlson , Pieper, Wiringa: PRC56(1997)1720

V_{ijk}: Effective three nucleon force

Hiyama, Gibson, Kamimura, PRC 70(2003)031001

Effective Interaction: MN (+Coulomb)

V_{ij}: Central+Coulomb

Thompson, LeMere, Tang, NPA(1977)286

The basis function for the sub-system is determined by SVM (MRM case)

potential	cluster	present				literature		
		N_k	E (MeV)	$R^{\rm rms}$ (fm)	P_D (%)	E (MeV)	$R^{\rm rms}$ (fm)	P_D (%)
AV8′ (with TNF)	$d(1^+)$	8	-2.18	1.79	5.9	-2.24	1.96	5.8
	$t(\frac{1}{2}^+)$	30	-8.22	1.69	8.4	-8.41	-	-
	$h(\frac{1}{2}^+)$	30	-7.55	1.71	8.3	-7.74	-	-
	^{4}He(0^+)	(2370)	-27.99	1.46	13.8	-28.44	-	14.1
MN	$d(1^+)$	4	-2.10	1.63	0	-2.20	1.95	0
	$t(\frac{1}{2}^+)$	15	-8.38	1.70	0	-8.38	1.71	0
	$h(\frac{1}{2}^+)$	15	-7.70	1.72	0	-7.71	1.74	0
	^{4}He(0^+)	(1140)	-29.94	1.41	0	-29.94	1.41	0

Hiyama

Horiuchi

present

Included channels in the present calculation

model			channel
FULL	$2N+2N$	I	$d(1^+)+d(1^+)$
			$d(1^+)+d^*(1^+)$
			$d^*(1^+)+d^*(1^+)$
		II	$\bar{d}(0^+)+\bar{d}(0^+)$
			$\bar{d}(0^+)+d^*(0^+)$
			$d^*(0^+)+d^*(0^+)$
		III	$d^*(2^+)+d^*(1^+)$
			$d^*(2^+)+d^*(2^+)$
		IV	$d^*(3^+)+d^*(1^+)$
			$d^*(3^+)+d^*(2^+)$
			$d^*(3^+)+d^*(3^+)$
		V	$2n(0^+)+2p(0^+)$
			$2n(0^+)+2p^*(0^+)$
			$2n^*(0^+)+2p(0^+)$
			$2n^*(0^+)+2p^*(0^+)$
	$3N+N$	1	$t(\frac{1}{2}^+)+p(\frac{1}{2}^+)$
			$t^*(\frac{1}{2}^+)+p(\frac{1}{2}^+)$
		2	$h(\frac{1}{2}^+)+n(\frac{1}{2}^+)$
			$h^*(\frac{1}{2}^+)+n(\frac{1}{2}^+)$

Thanks to the reduction of basis function by SVM for the sub-system. We can reduce the dimension of matrix elements very much!

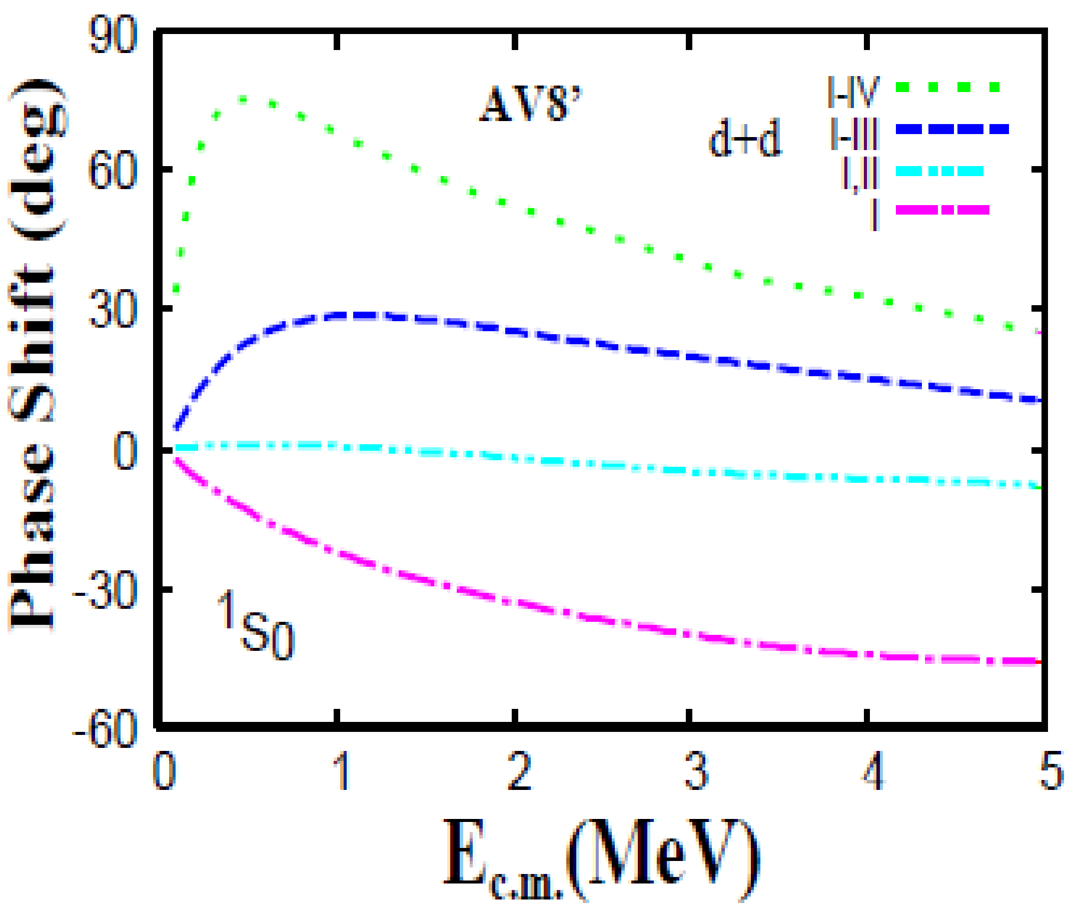
Dimensions of matrix elements for FULL in the LS-coupled case

0+	6660
1+	16680
2+	22230
0-	4200
1-	11670
2-	12480

For 2+, it takes about 200 days with 1CPU(1Core). And we need about 20Gbyte memory for the MRM calculation.

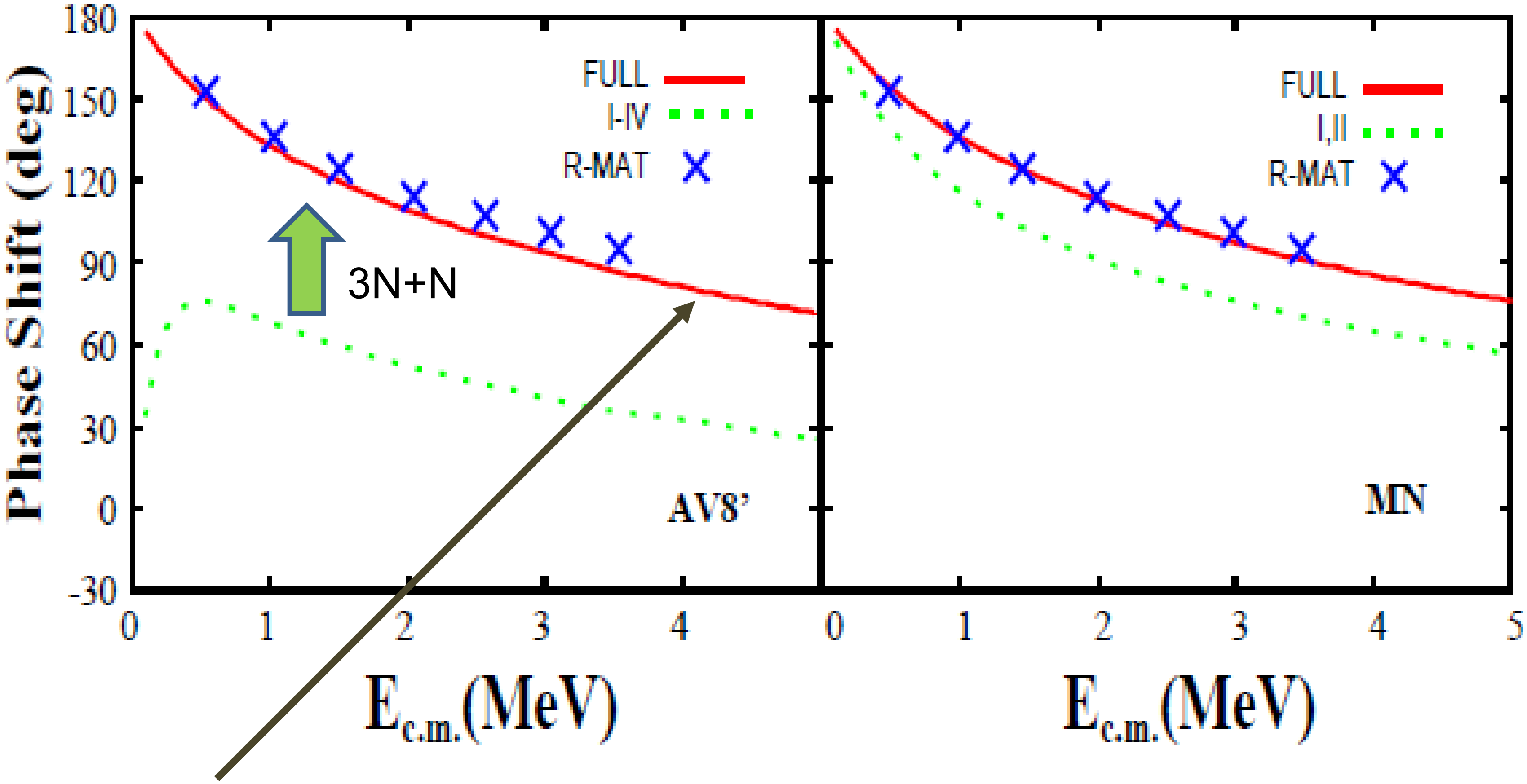
All pseudo states (discretized continuum state) are employed in the MRM calculation.

$^1S_0$ d+d elastic phase shift within d+d channel



	channel
I	$d(1^+)+d(1^+)$
	$d(1^+)+d^*(1^+)$
	$d^*(1^+)+d^*(1^+)$
II	$\bar{d}(0^+)+\bar{d}(0^+)$
	$\bar{d}(0^+)+d^*(0^+)$
	$d^*(0^+)+d^*(0^+)$
III	$d^*(2^+)+d^*(1^+)$
	$d^*(2^+)+d^*(2^+)$
IV	$d^*(3^+)+d^*(1^+)$
	$d^*(3^+)+d^*(2^+)$
	$d^*(3^+)+d^*(3^+)$

$^{1}S_{0}$ d+d elastic phase shift (0+)

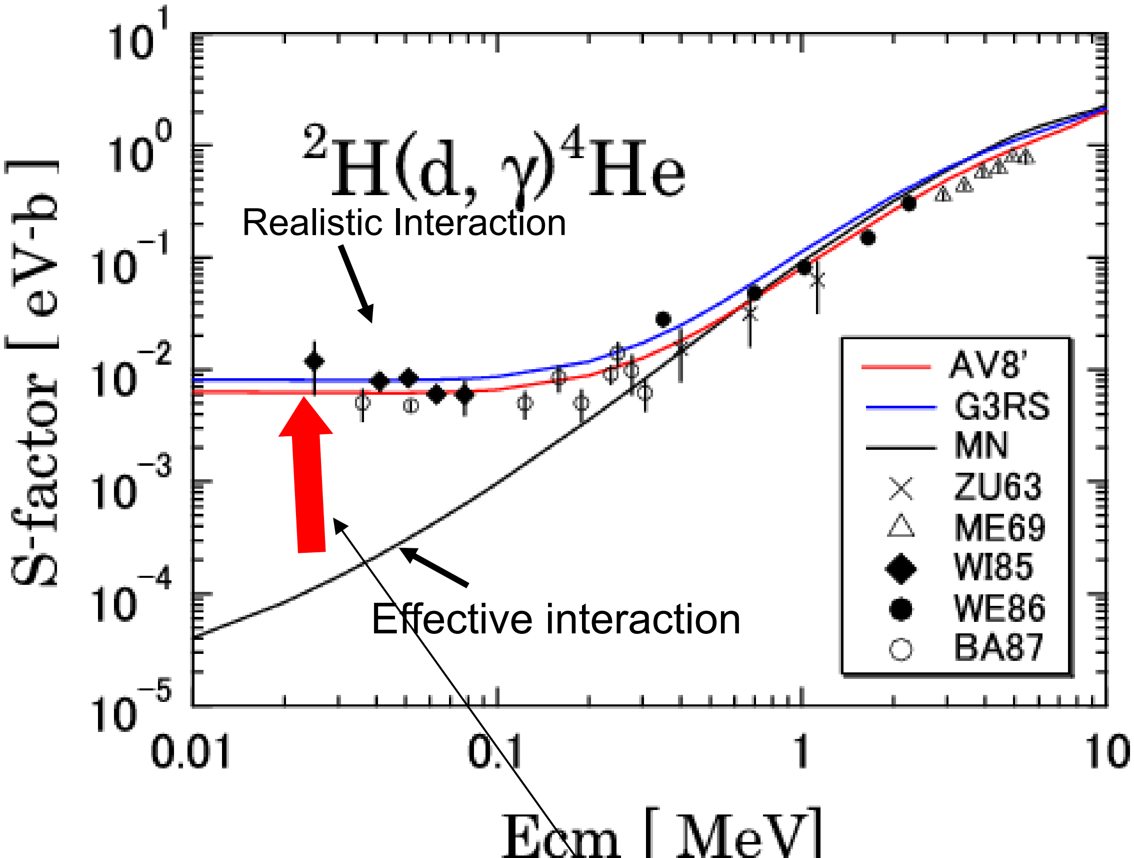


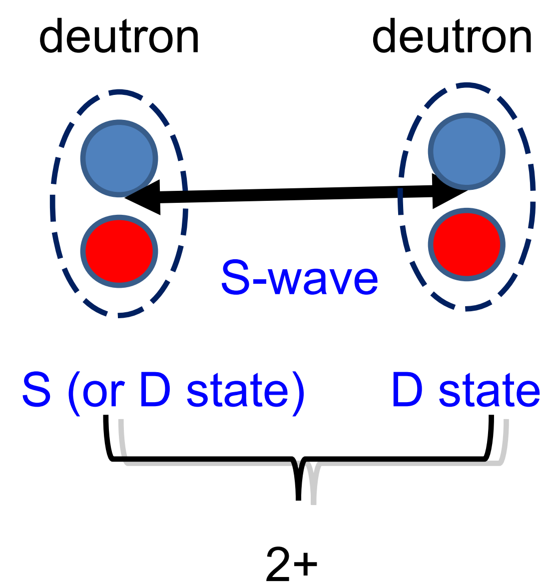
For effective interaction, d+d scattering picture is good!

R.-Matrix analyses : Hofmann, Hale, PRC77(2008)044002

Radiative capture

K. Arai, S. Aoyama, Y. Suzuki, P. Descouvemont and D. Baye, PRL107 (2011) 132502.



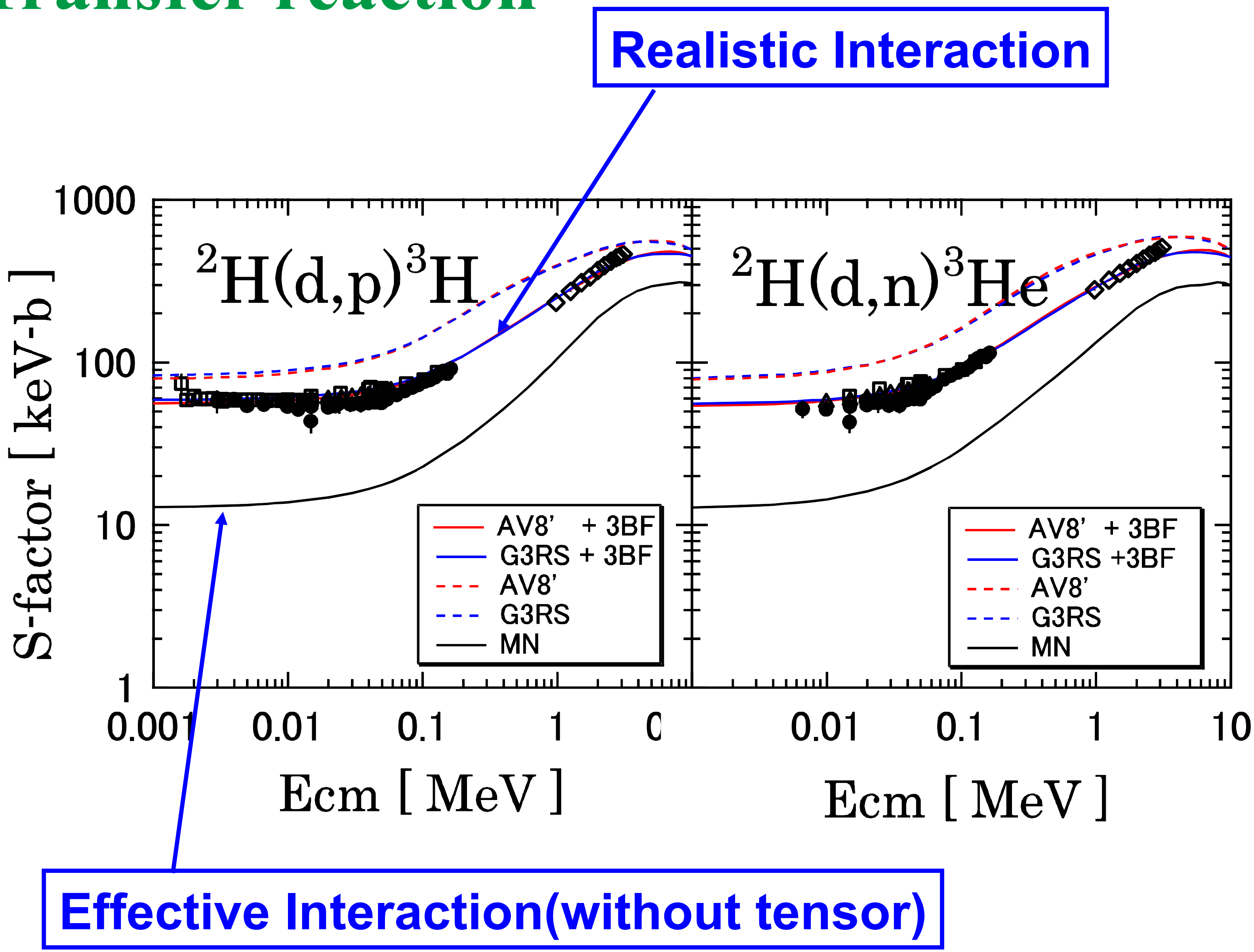


E2 transition is not reduced so much because of d-wave component.

d(1+;T=0) + d(1+;T=0) => ^{4}He (T=0) + γ

We can add a new evidence of D-wave components (tensor) of deutron and ^{4}He.

Transfer reaction



K. Arai, S. Aoyama, Y. Suzuki, P. Descouvemont and D. Baye, PRL107 (2011) 132502.

Complex Scaling Method

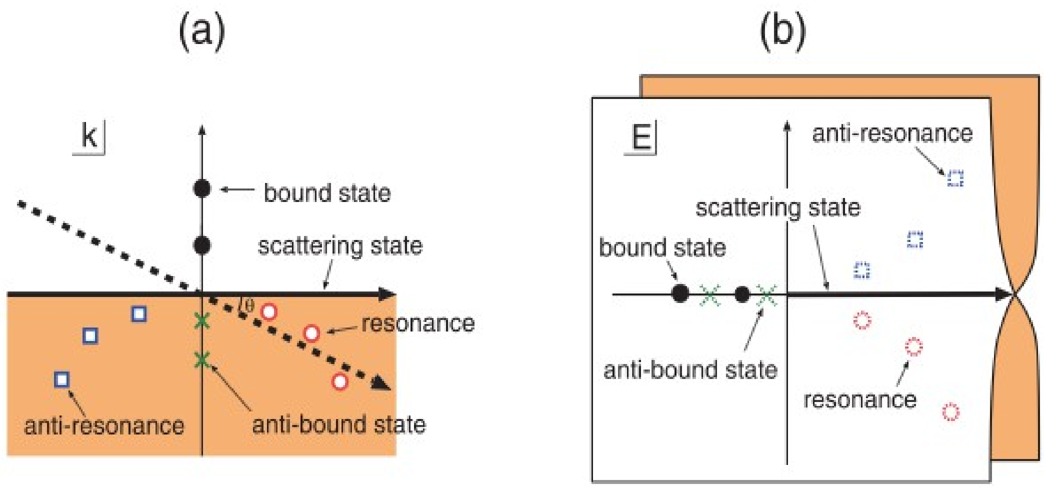
Gyarmati, Vertse, NPA160(1971)269
Aguilar, Combes, CMP22(1971)269,
Balslev, Combes, CMP22(1971)280

$$U(\theta)r = re^{i\theta}, \quad U(\theta)k = ke^{-i\theta}.$$ Complex scaling

$$H(\theta)\Psi(\theta) = E(\theta)\Psi(\theta),$$ Schrodinger Equation

$$H(\theta) = U(\theta)HU(\theta)^{-1},$$ Hamiltonian

$$\Psi(\theta) = U(\theta)\Psi = e^{\frac{3}{2}i\theta}\Psi(re^{i\theta}).$$ Wave Function



$$e^{ik_R\cdot re^{i\theta}} = e^{i(\kappa_r - i\gamma_r)re^{i\theta}} = e^{ir(\kappa_r - i\gamma_r)(\cos\theta + i\sin\theta)}$$

$$= e^{(-\kappa_r\sin\theta + \gamma_r\cos\theta)r}\cdot e^{i(\kappa_r\cos\theta + \gamma_r\sin\theta)r}.$$

Dumping wave function (L^2) for large scaling angle

Review: S. Aoyama, T.Myo, K. Kato and K. Ikeda Prog. Theor. Phys., 116 (2006).

Extended completeness relation in CSM

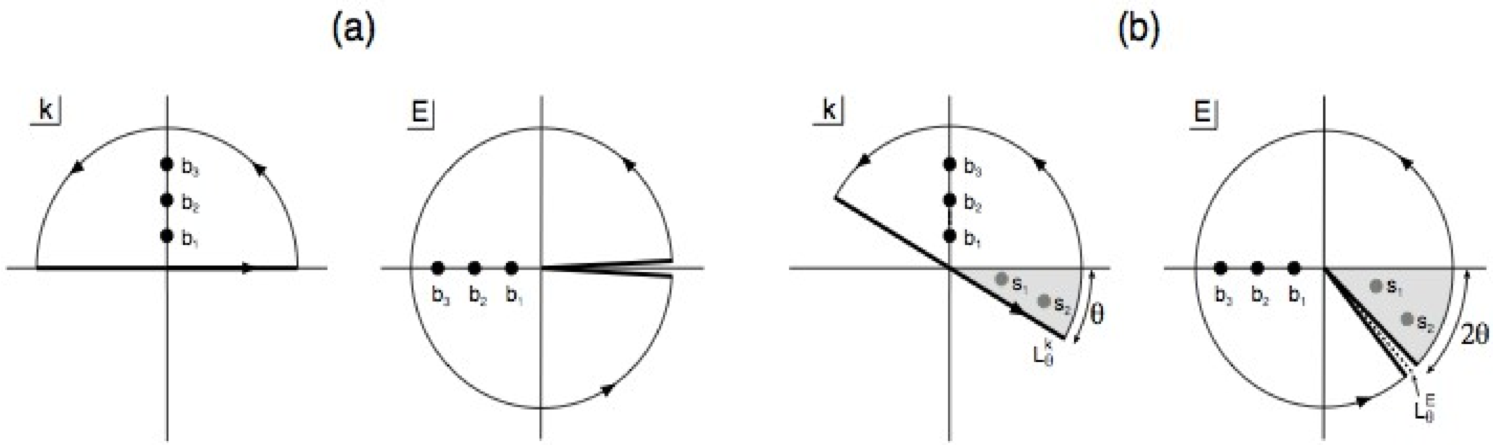


Fig. 7. The Cauchy integral contours in the momentum and energy planes for the completeness relation (a) without and (b) with the complex scaling method. b_1, b_2, $\cdots$ and s_1, s_2, $\cdots$ are the bound and resonant poles, respectively.

$$
\begin{aligned}
1 &= \sum_b |\chi_b\rangle\langle\chi_b| + \int_0^\infty dE|\chi_E\rangle\langle\chi_E|, \\
&= \sum_b |\chi_b\rangle\langle\chi_b| + \int_{-\infty}^{+\infty} dk|\chi_k\rangle\langle\chi_k|,
\end{aligned}
$$

$$
\begin{aligned}
1 &= \sum_b |\chi_b^\theta)(\tilde{\chi}_b^\theta| + \sum_r^{n_r^\theta} |\chi_r^\theta)(\tilde{\chi}_r^\theta| + \int_{L_\theta^E} dE|\chi_E^\theta)(\tilde{\chi}_E^\theta|, \\
&= \sum_b |\chi_b^\theta)(\tilde{\chi}_b^\theta| + \sum_r^{n_r^\theta} |\chi_r^\theta)(\tilde{\chi}_r^\theta| + \int_{L_\theta^k} dk|\chi_k^\theta)(\tilde{\chi}_k^\theta|,
\end{aligned}
$$

Review: S. Aoyama, T.Myo, K. Kato and K. Ikeda Prog. Theor. Phys., 116 (2006).

Three-body example of complex eigenvalue distributions

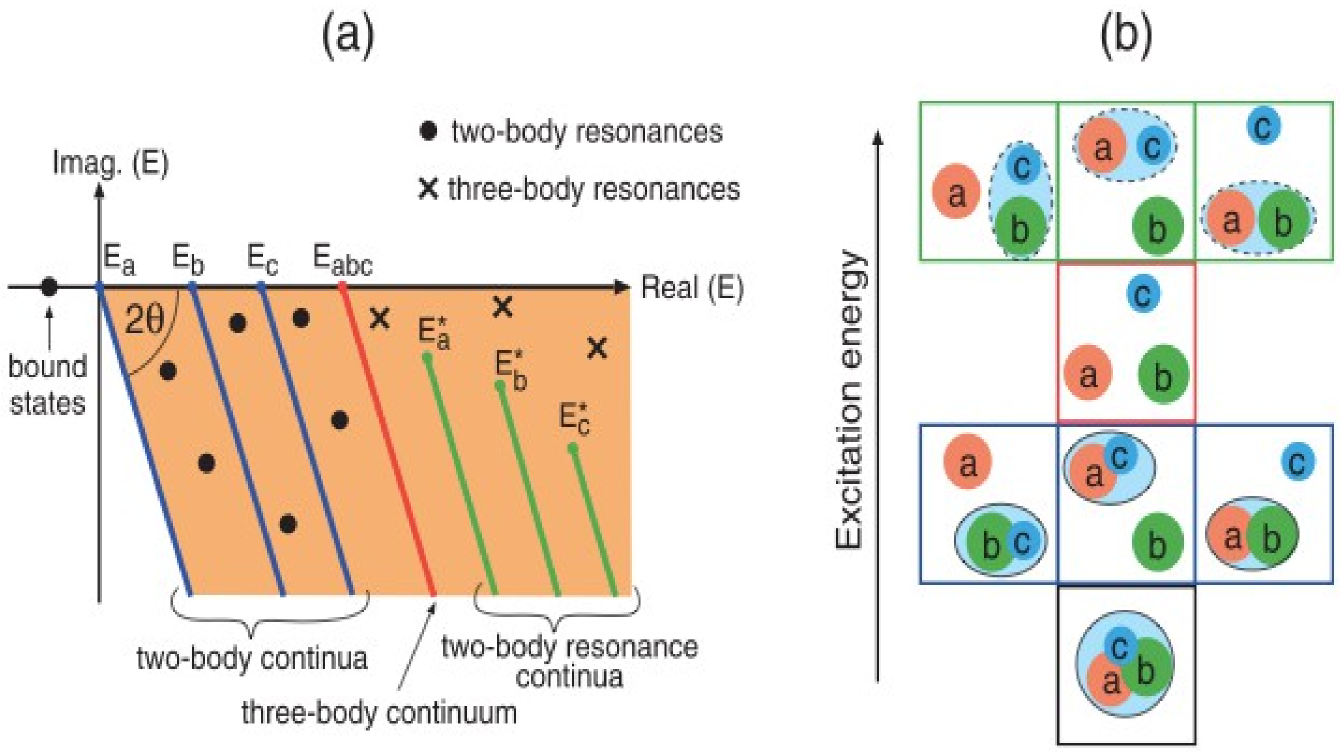
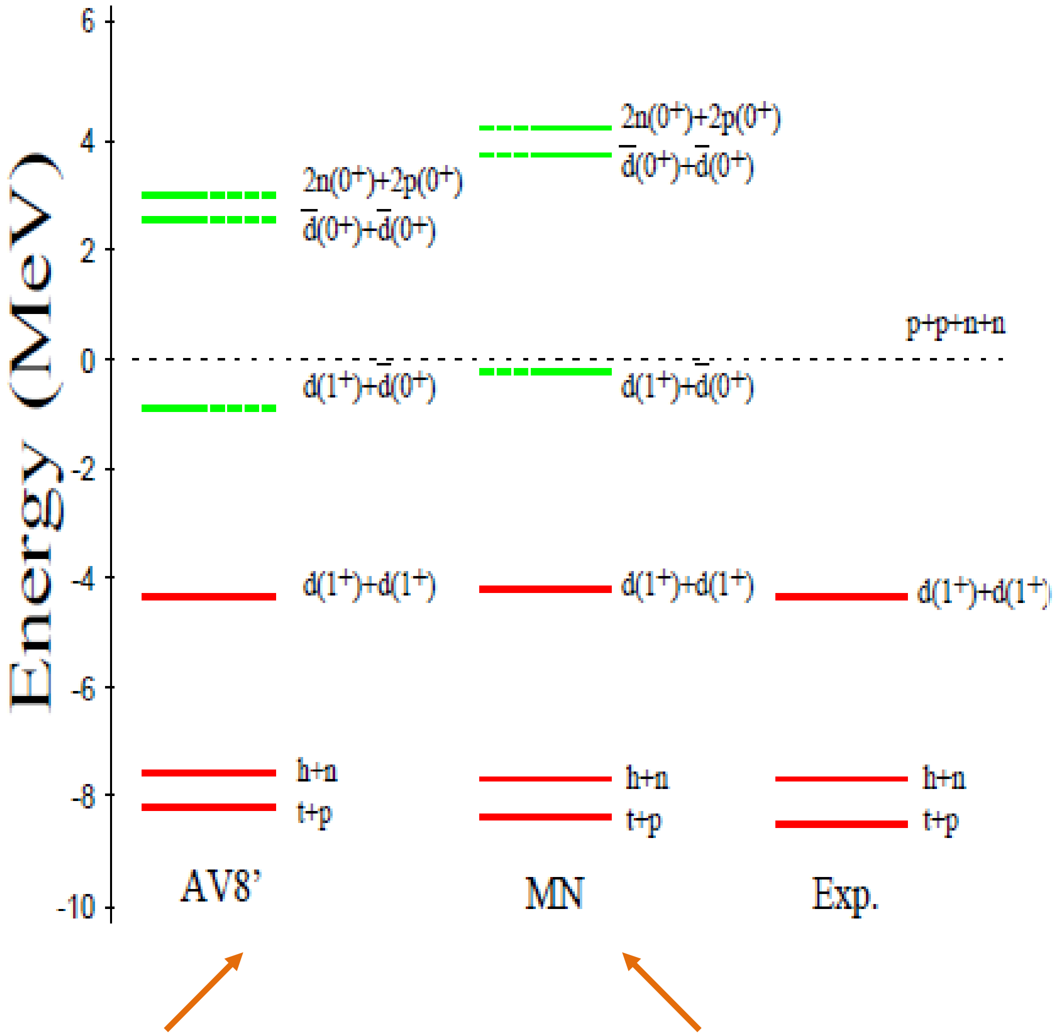


Fig. 5. Schematic eigenvalue distribution of the complex scaled Hamiltonian $H(\theta)$ for a three-body system. For details, see the main text.

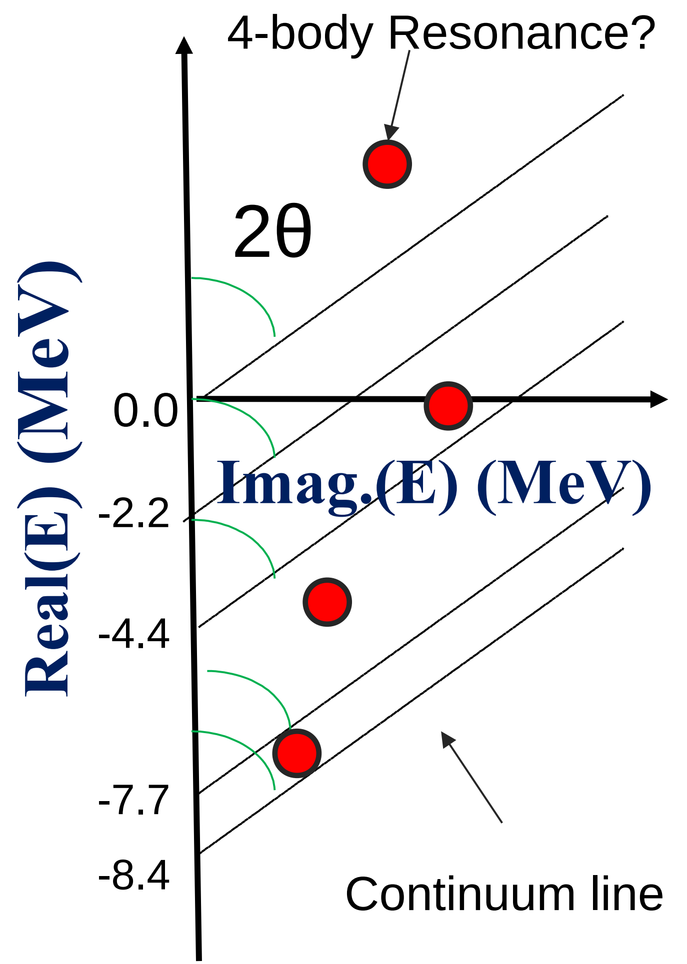
Review: S. Aoyama, T.Myo, K. Kato and K. Ikeda Prog. Theor. Phys., 116 (2006).

Threshold in ^{4}He



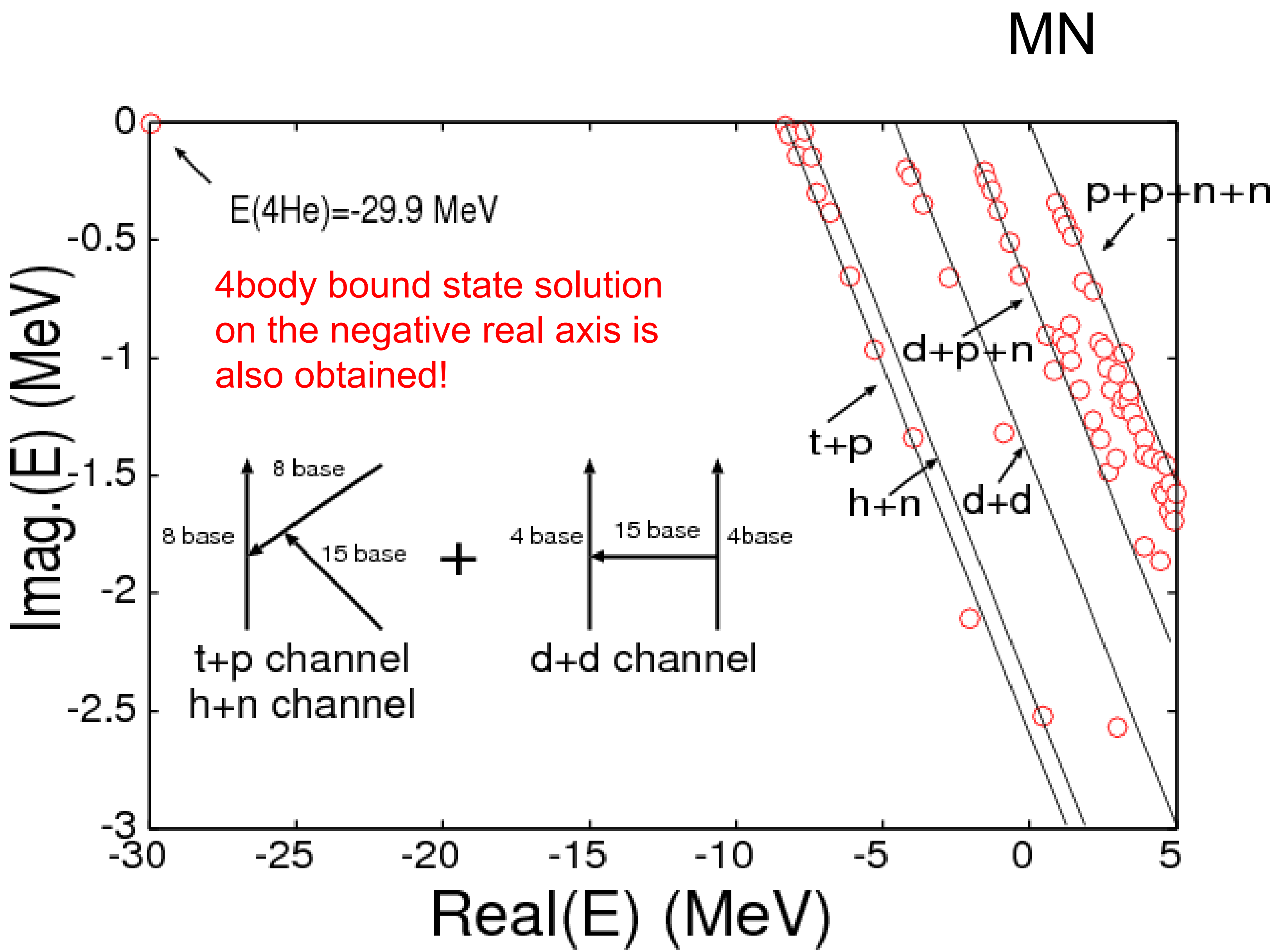
with three-nucleon force

without three-nucleon force



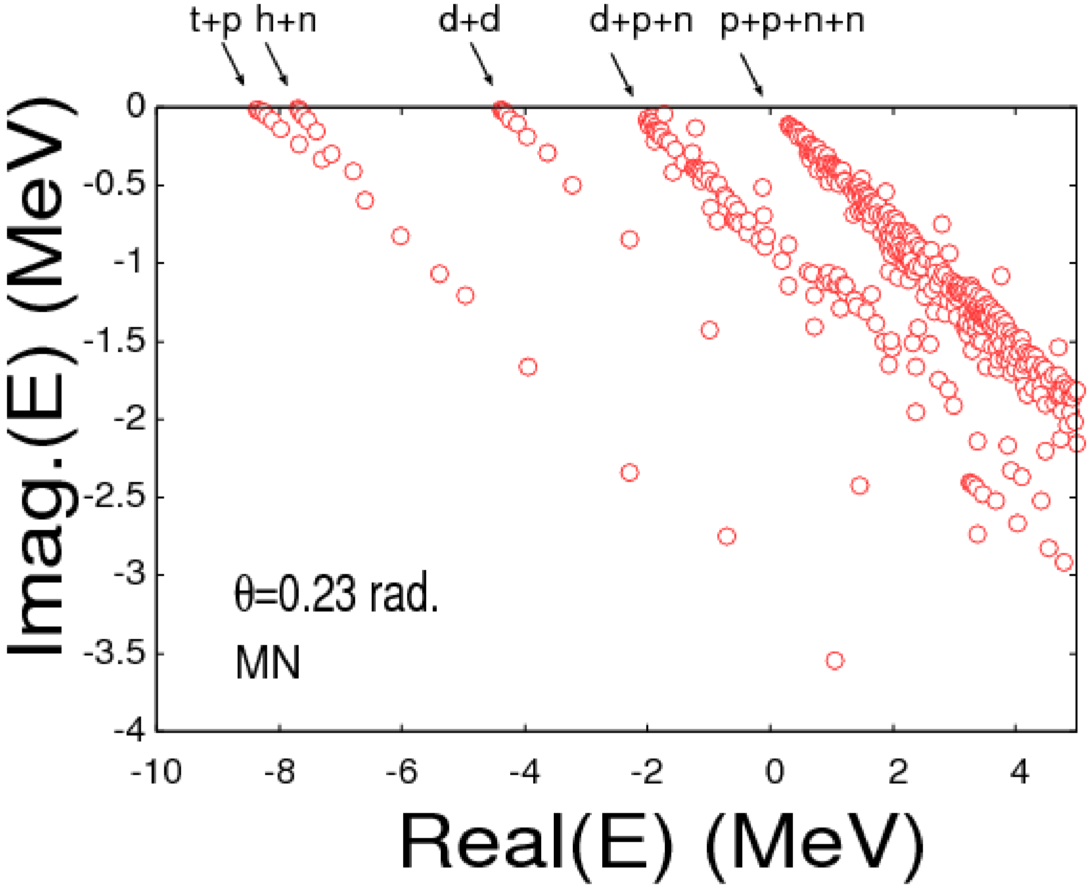
Eigenvalue Distribution in CSM

p+p+n+n case



MN
E(4He)=-29.9 MeV
4body bound state solution
on the negative real axis is
also obtained!
p+p+n+n
d+p+n
t+p
h+n
d+d
8 base
8 base
15 base
4 base
15 base
4base
+
t+p channel
h+n channel
d+d channel
Imag.(E) (MeV)
Real(E) (MeV)
0
-0.5
-1
-1.5
-2
-2.5
-3
-30
-25
-20
-15
-10
-5
0
5

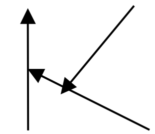
Complex Eigenvalue distribution of ^{4}He (0^+)



MN

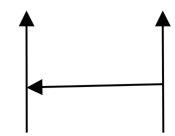
12,500 dimension.

K-type



+

H-type



How to search resonant solutions?

1. b-trajectory, N-trajectory method <= Kruppa, Kato, PTP84(1990)1145.
2. ACCC+ CSM <= Aoyama, PRC 68 (2003), 034313.

We need large calculations with massive parallel machines.

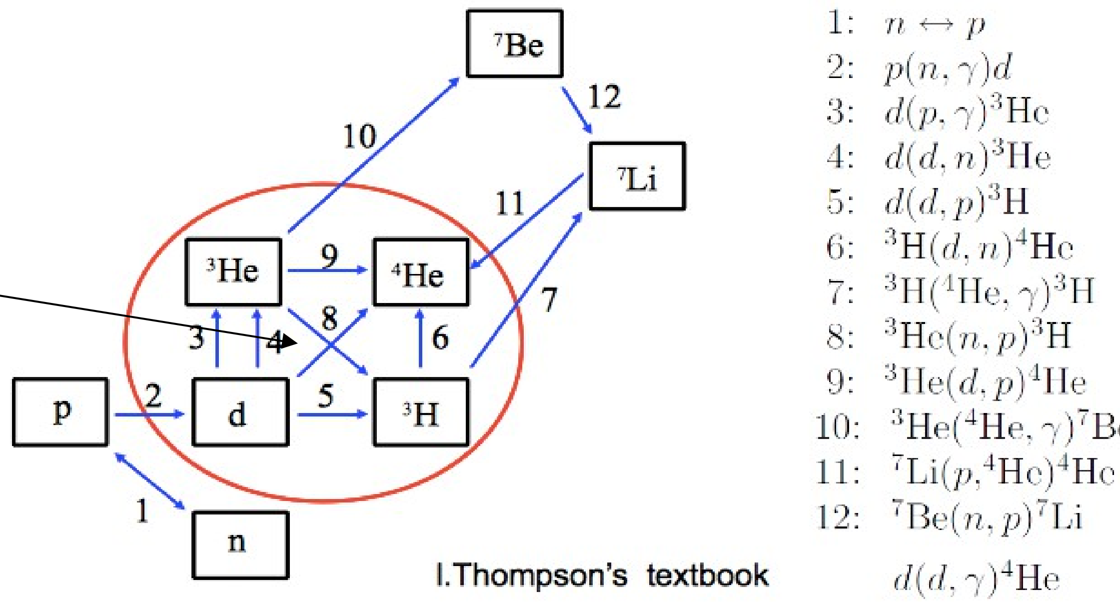
Summary

1. The distortion of the deuteron cluster for $^1S_0$ due to the tensor interaction is very large.

2. Astrophysical S-factor is strongly influenced by the tensor interaction.

In Big-Bang, the tensor interaction plays a crucial role!?

Ab-initio
3,4,5-body reaction
physics is here!



Application of complex scaling method is also in progress.