(微視的) チャネル結合法を用いた直接核反応の研究

北大情報基盤センター

平林義治

○入射粒子-標的核系の直接反応（弾性・非弾性散乱、分解反応）

→ Coupled-Channels method

○核（入射核、標的核）の内部波動関数を（なるべく）微視的に

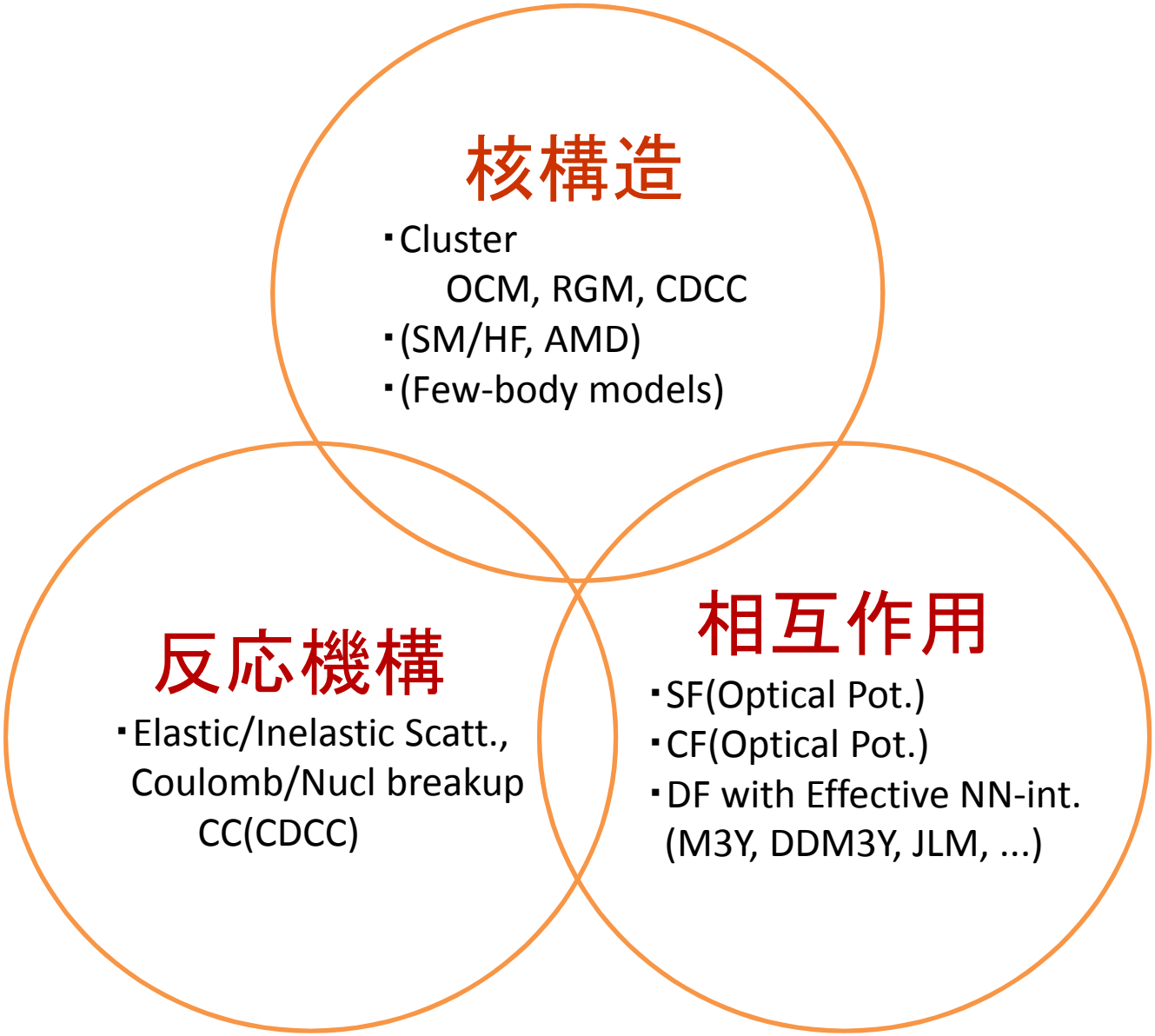
→ (CC)OCM, RGM, CDCC

○反応系（入射核＋標的核間）の相互作用

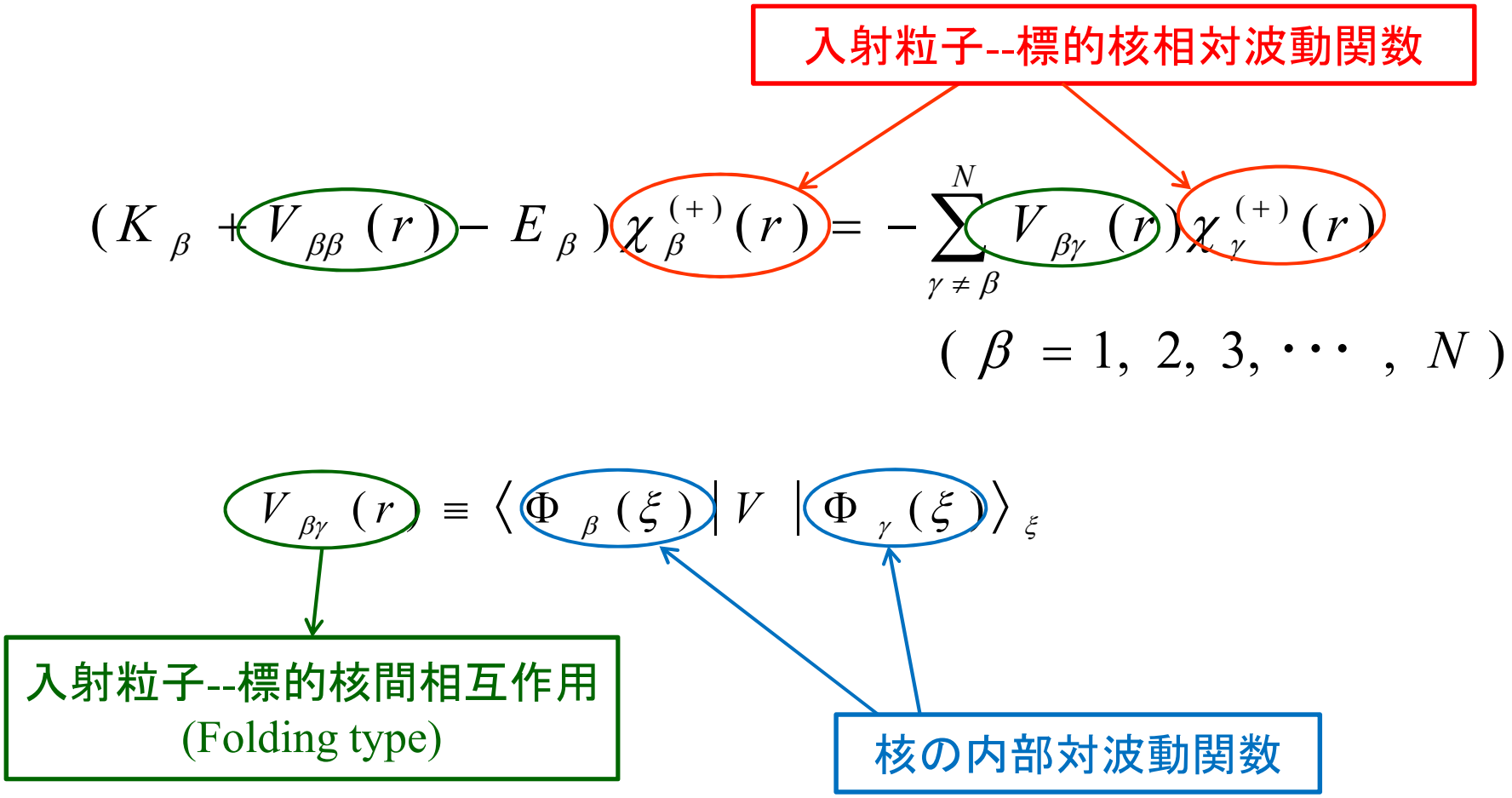
核力・Coulomb力の diagonal, off-diagonal(coupling) potential

→ Folding type (SF, CF, DF(M3Y, DDM3Y, JLM, ...))

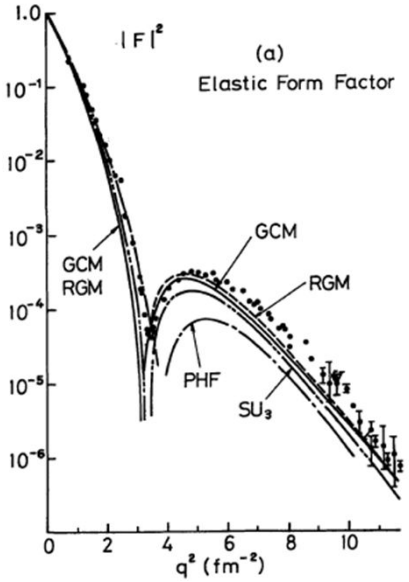
○微視的チャネル結合法


核構造
・Cluster
OCM, RGM, CDCC
・(SM/HF, AMD)
・(Few-body models)
反応機構
・Elastic/Inelastic Scatt.,
Coulomb/Nucl breakup
CC(CDCC)
相互作用
・SF(Optical Pot.)
・CF(Optical Pot.)
・DF with Effective NN-int.
(M3Y, DDM3Y, JLM, ...)

○Coupled-Channels Equations

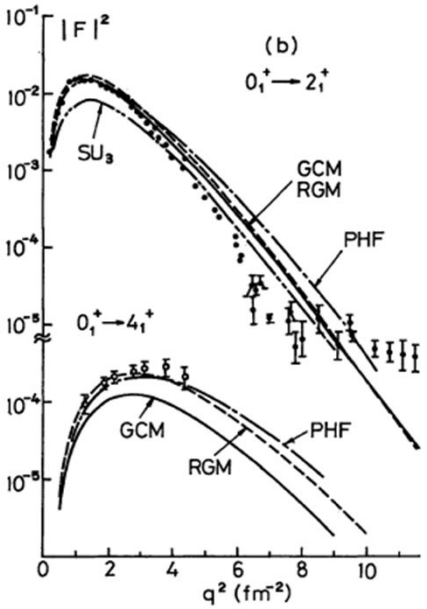


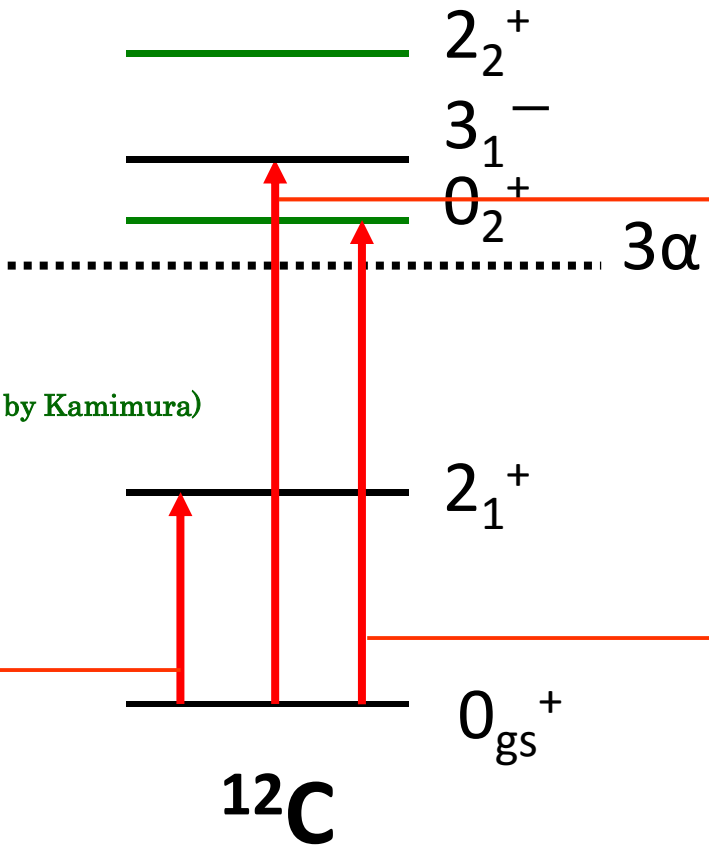
○　核（入射粒子、標的核）の微視的波動関数（例：^{12}C）

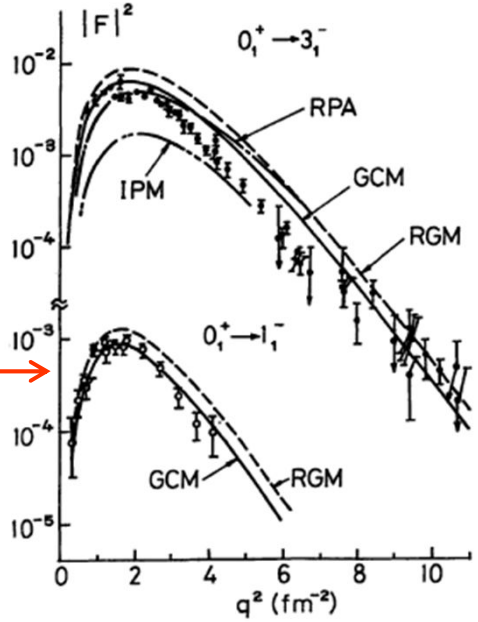


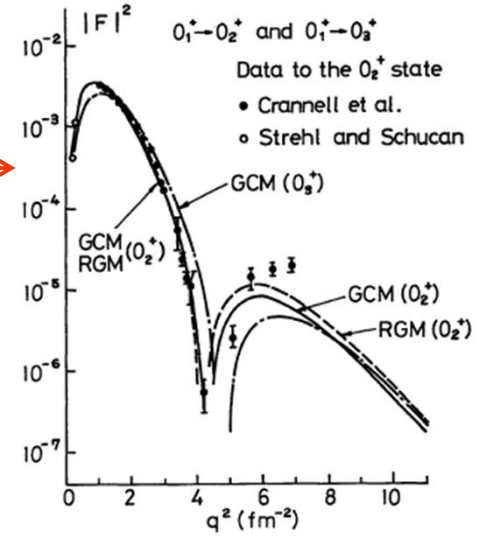
電子散乱形状因子の実験・理論比較

PTP Suppl. 68 , '80 (GCM by Uegaki, RGM by Kamimura)





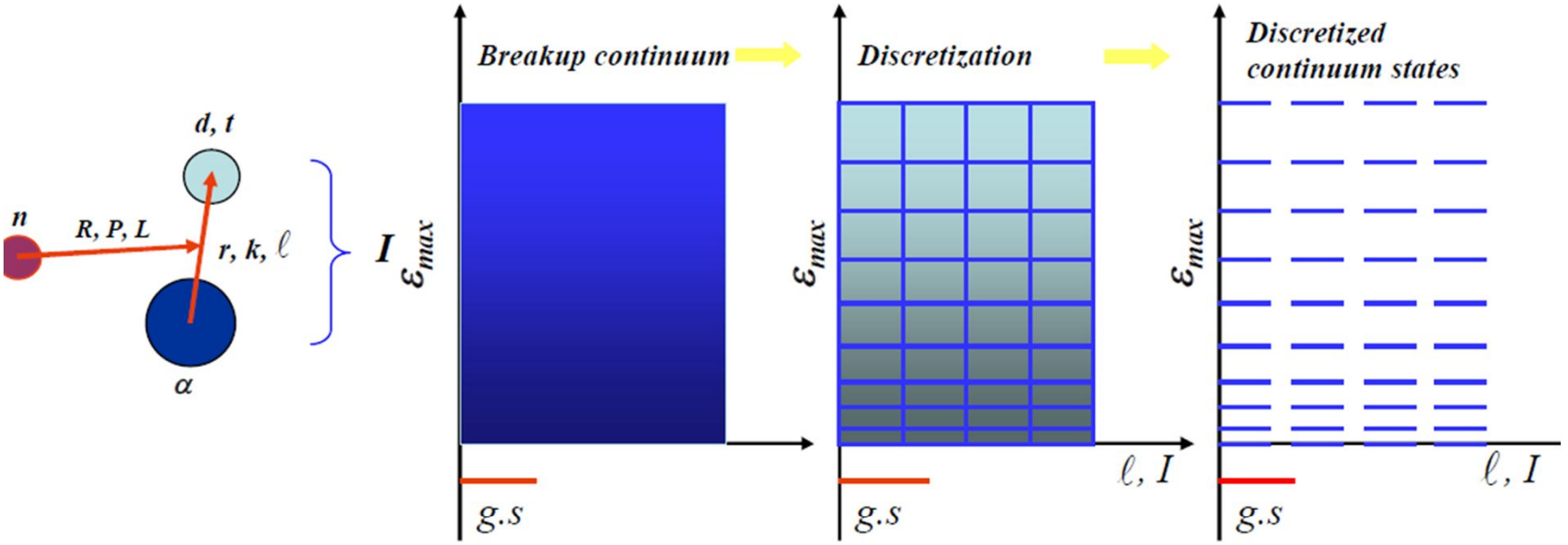




構造遷移が正しく記述されていることが非常に重要

○　核の微視的波動関数（例：CDCC）

The Method of CDCC in ^{6,7}Li



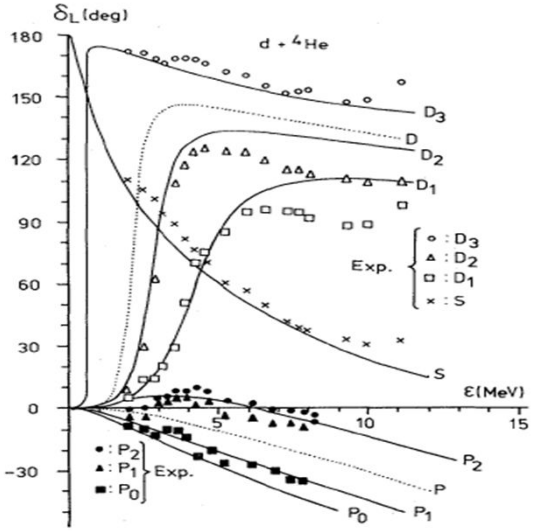
$$\Psi_{JM}(\vec{r},\vec{R}) = \sum_{L} Y_{JM}^{\ell_0 I_0 L}\phi_0(r)\chi_{\ell_0 I_0 LJ}(P_0,R)/R + \sum_{\ell,I,L} Y_{JM}^{\ell I L}\int_0^{\infty}\phi_{\ell I}(k,r)\chi_{\ell I L J}(P,R)/R\,dk,$$

After the discretization,

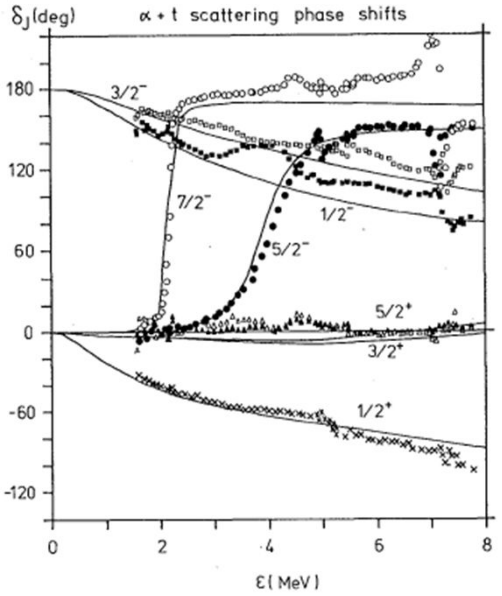
$$\Psi_{JM}^{CDCC}(\vec{r},\vec{R}) = \sum_{L} Y_{JM}^{\ell_0 I_0 L}\phi_0(r)\hat{\chi}_{\gamma_0}(P_0,R)/R + \sum_{i=1}^{N}\sum_{\ell=0}^{\ell_{\max}}\sum_{I}\sum_{L} Y_{JM}^{\ell I L}\hat{\phi}_{i\ell I}(r)\hat{\chi}_{\gamma}(\hat{P}_{\gamma},R)/R,$$

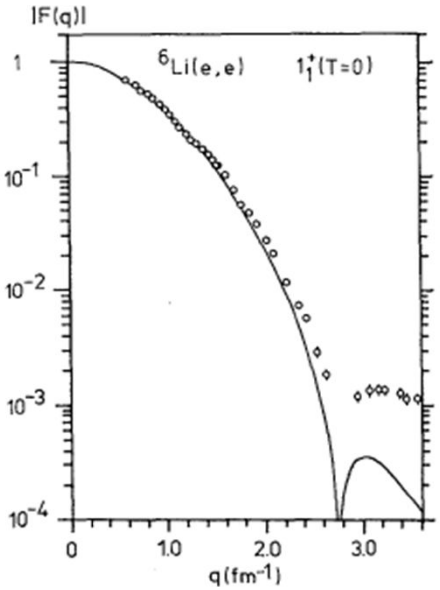
○　核の微視的波動関数（例：CDCC ^{6,7}Li）

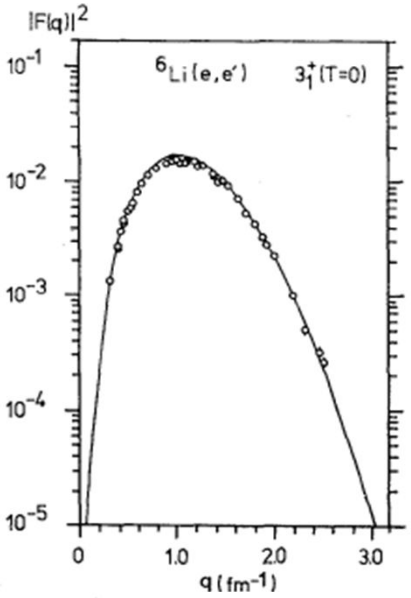
scattering phase shifts & charge form factors の再現

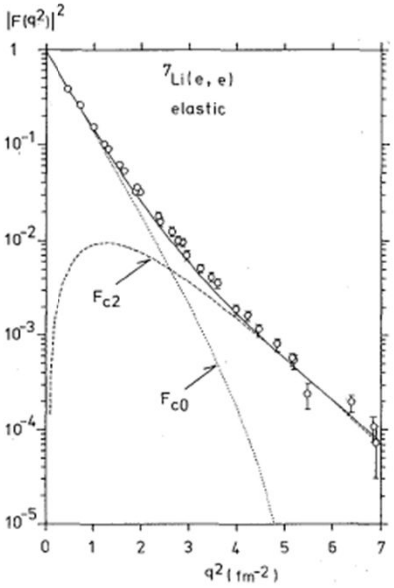


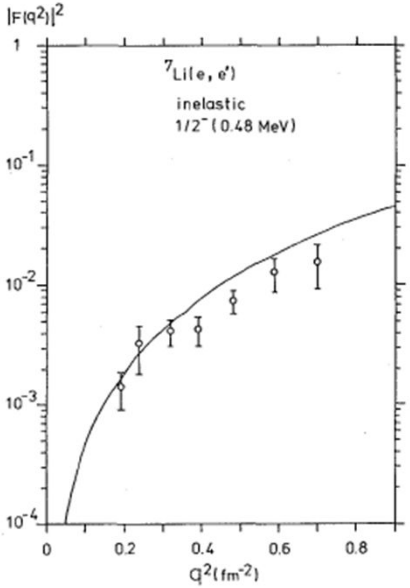
Y.Sakuragi, PTP Suppl. 89 ('86) 136





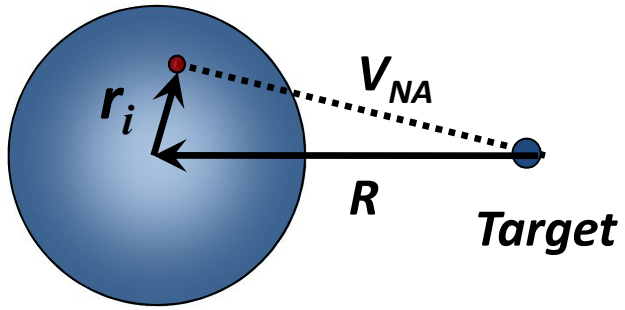




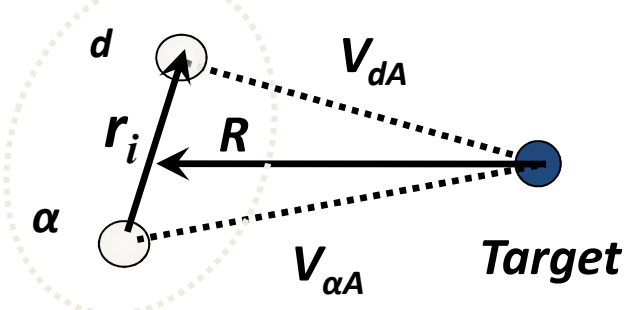


○　入射核--標的核間相互作用　　diagonal & coupling potentials

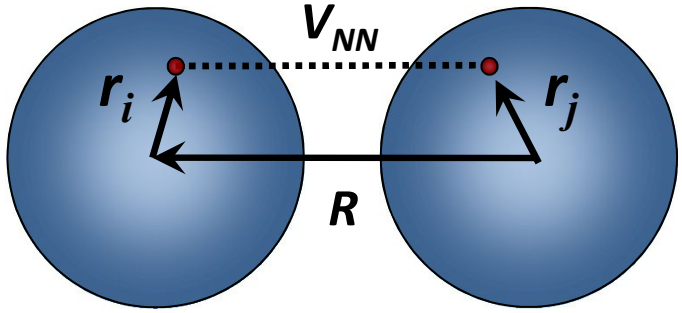
Single-Folding Model (SFM)



Cluster-Folding Model (CFM)



Double-Folding Model (DFM)



$$V_{SFM}(R) = \int \rho_p(\vec{r}_1)\, V_{NA}^{(opt)}(\vec{R} - \vec{r}_1)\, d\vec{r}_1$$

V_{NA}: N--核 optical potential

$$V_{CFM}(\vec{R}) = \left\langle \varphi(\vec{r}) \left| V_{d-A}(\vec{R} + \tfrac{m_d}{M}\vec{r}) + V_{\alpha-A}(\vec{R} - \tfrac{m_\alpha}{M}\vec{r}) \right| \varphi(\vec{r}) \right\rangle$$

V_{CA}: Cluster--核 optical potential

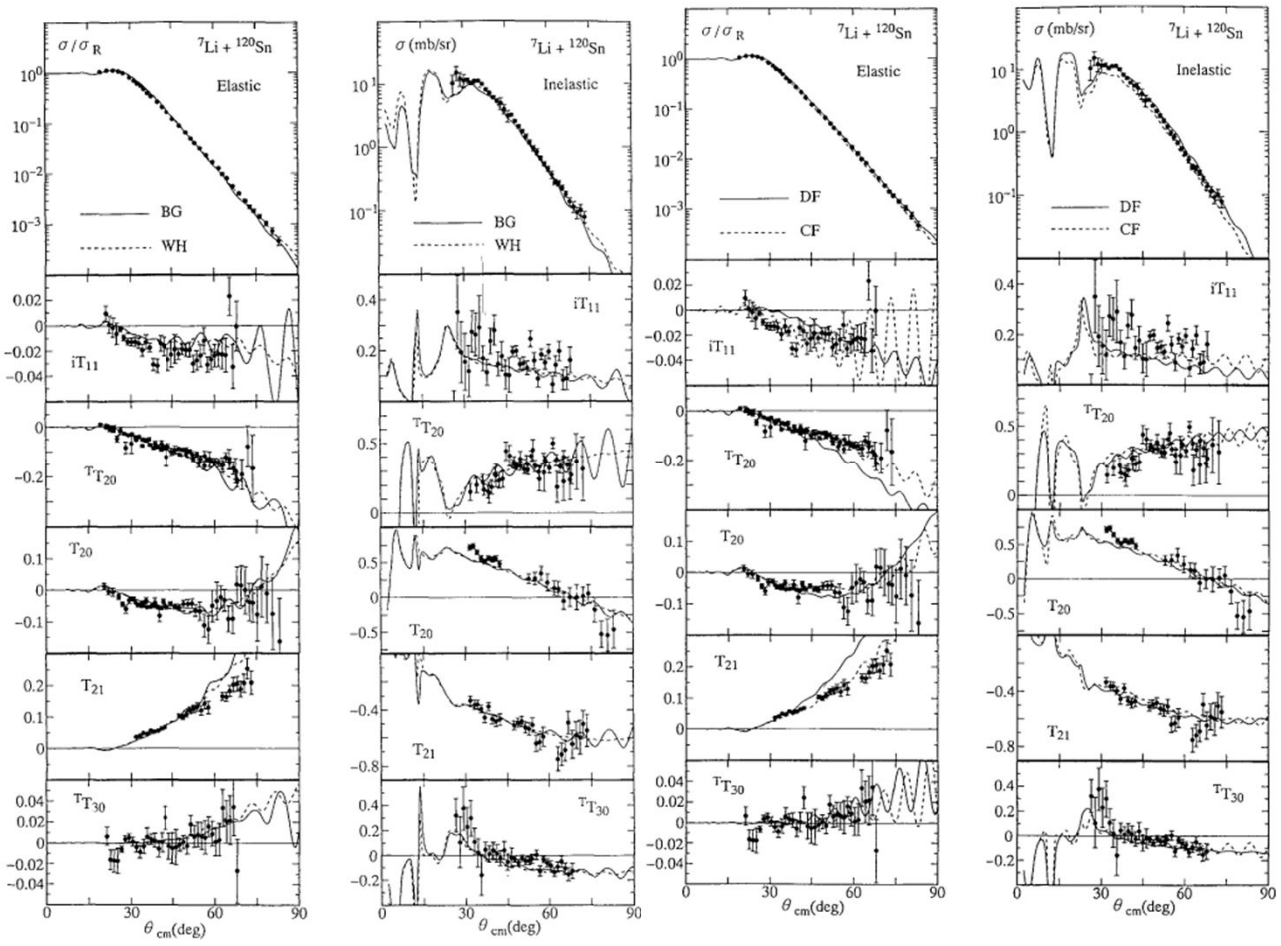
$$V_{DFM}(R) = \int \rho_p(\vec{r}_1)\rho_t(\vec{r}_2)\, v_{NN}(\vec{R} + \vec{r}_1 - \vec{r}_2)\, d\vec{r}_1\, d\vec{r}_2$$

V_{NN}: effective N-N interaction (M3Y, DDM3Y, JLM)

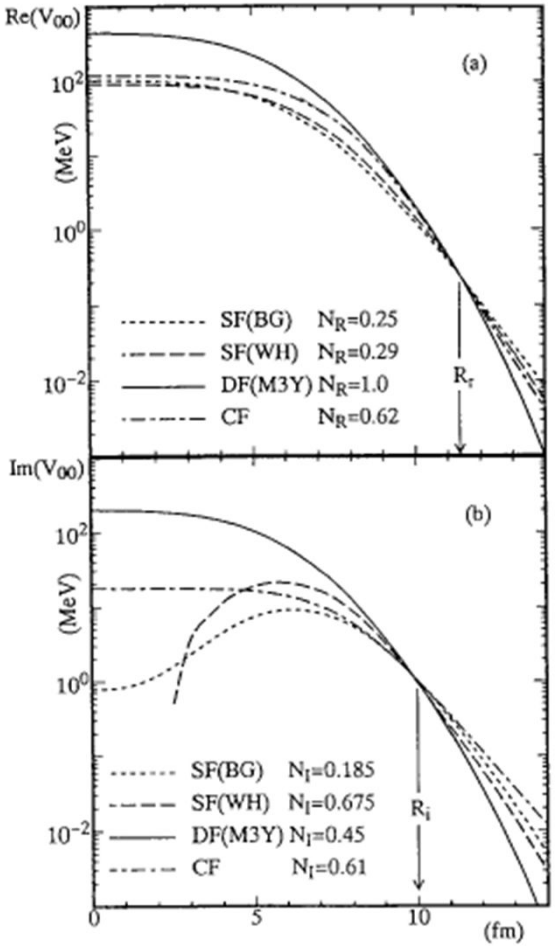
$$\rho_{ik}(\vec{r}) = \left\langle \varphi_i(\xi) \left| \sum_i \delta(\vec{r}_i - \vec{r}) \right| \varphi_k(\xi) \right\rangle$$

○偏極量における folding potential type (SF, CF, DF)の違い　CDCC

Y.H., Sakuragi, Tanifuji, PLB318 ('93) 32　　7Li + 120Sn, E(lab) = 44 MeV



SF　　CF, DF



diagonal part of SF, CF, DF pot.

○ Cluster Folding model の不具合（低エネルギー散乱） CDCC

Volume 258, number 1,2 PHYSICS LETTERS B 4 April 1991

Anomalous renormalization of cluster-folding interactions for ^{6}Li–nucleus scattering at low energies

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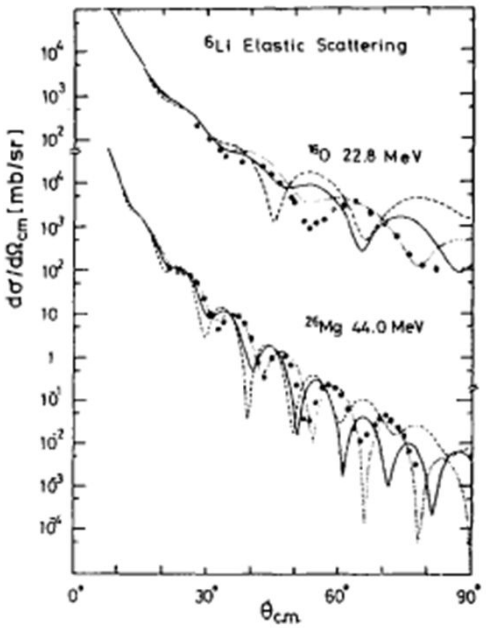
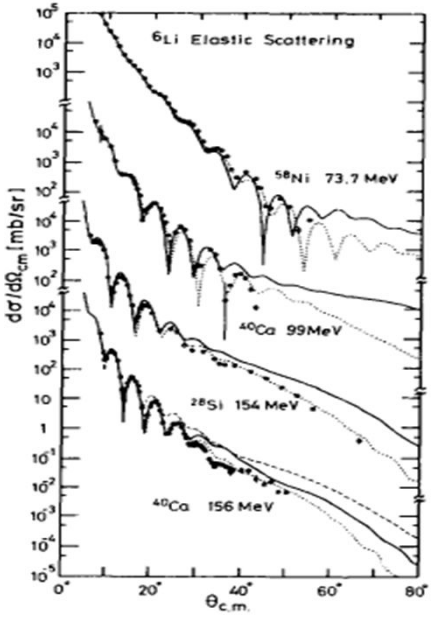
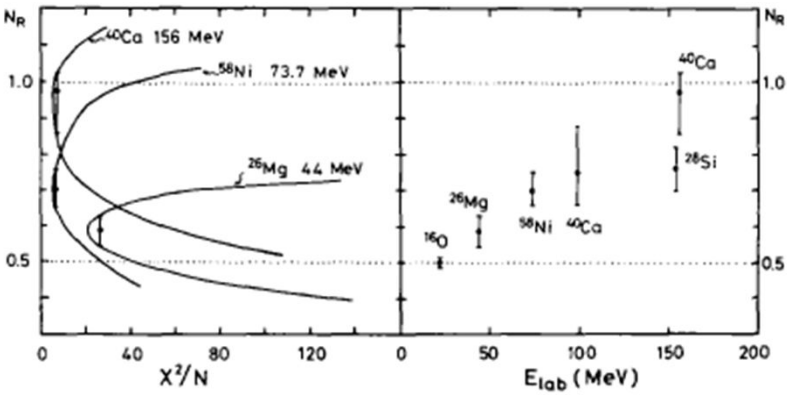


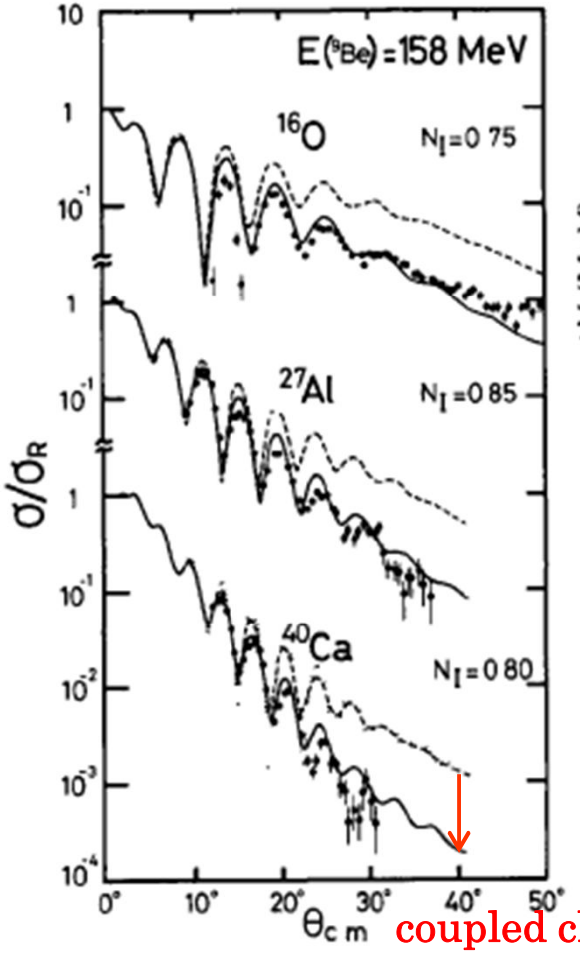


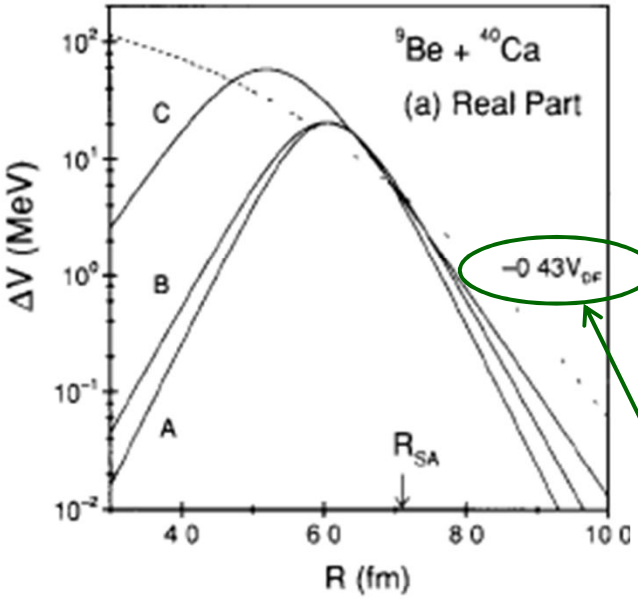


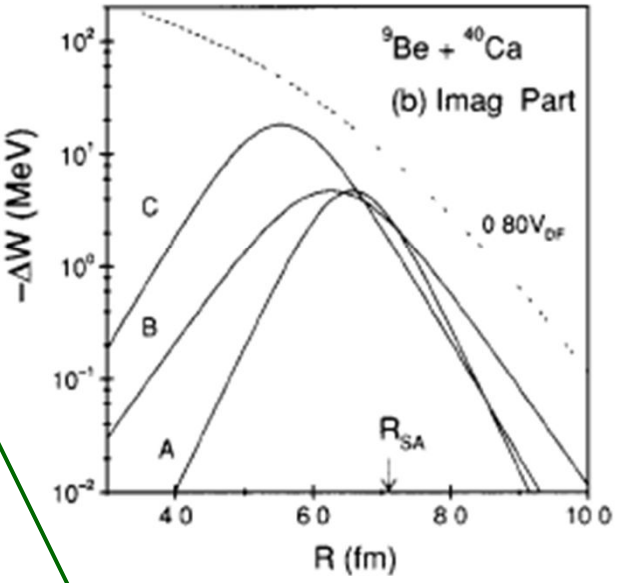
○ ^{9}Be 弾性散乱の角分布における分解過程の寄与と

dynamical polarization （動的分極）potential　　Microscopic CC

Y.H., Okabe, Sakuragi, PLB221 ('89) 227







$$V_{opt} = V_{00} + \sum_{\alpha,\alpha'} V_{0\alpha} \frac{1}{E - H_{QQ} + i\varepsilon} V_{\alpha' 0}$$

coupled channel の効果

（分解過程の寄与）

dynamic polarization potential

取り入れなかった模型空間(Q)の寄与

◆ Double Folding Model と Dynamic Polarization Potential

FOLDING MODEL POTENTIALS FROM REALISTIC INTERACTIONS FOR HEAVY-ION SCATTERING

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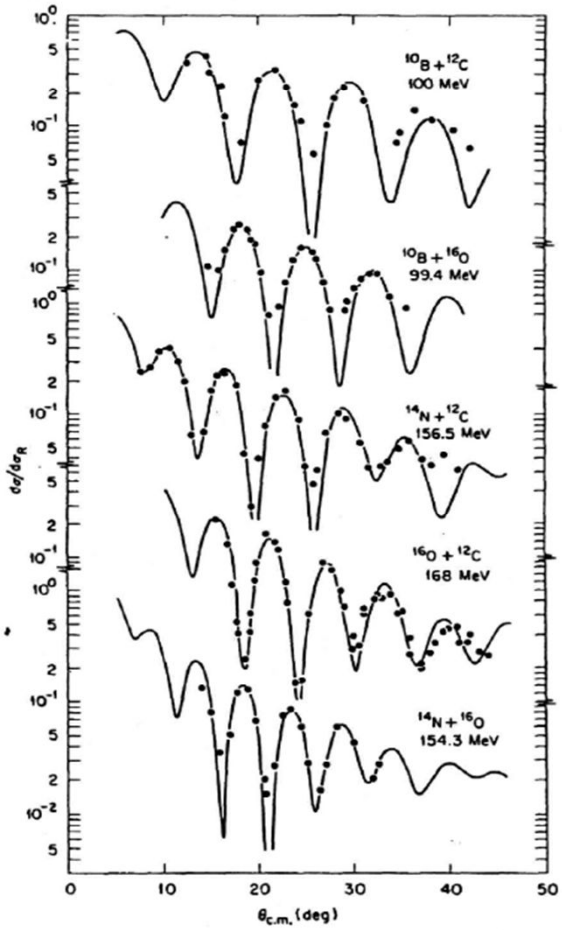
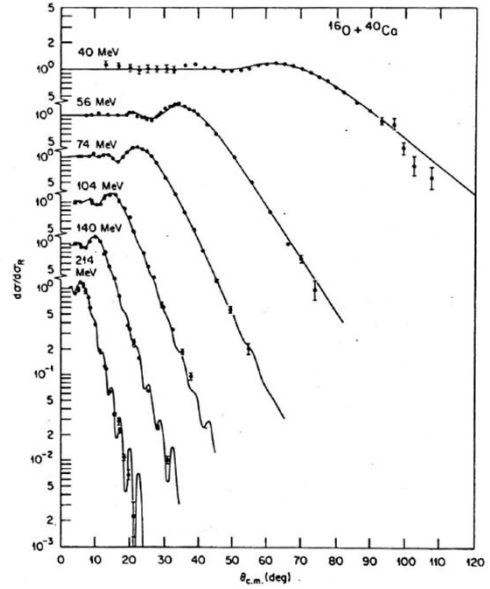
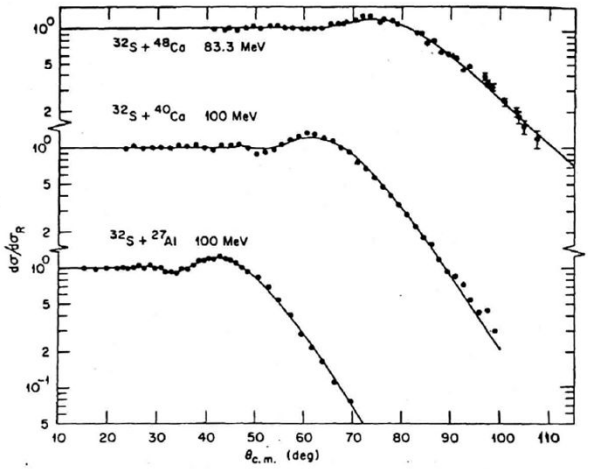
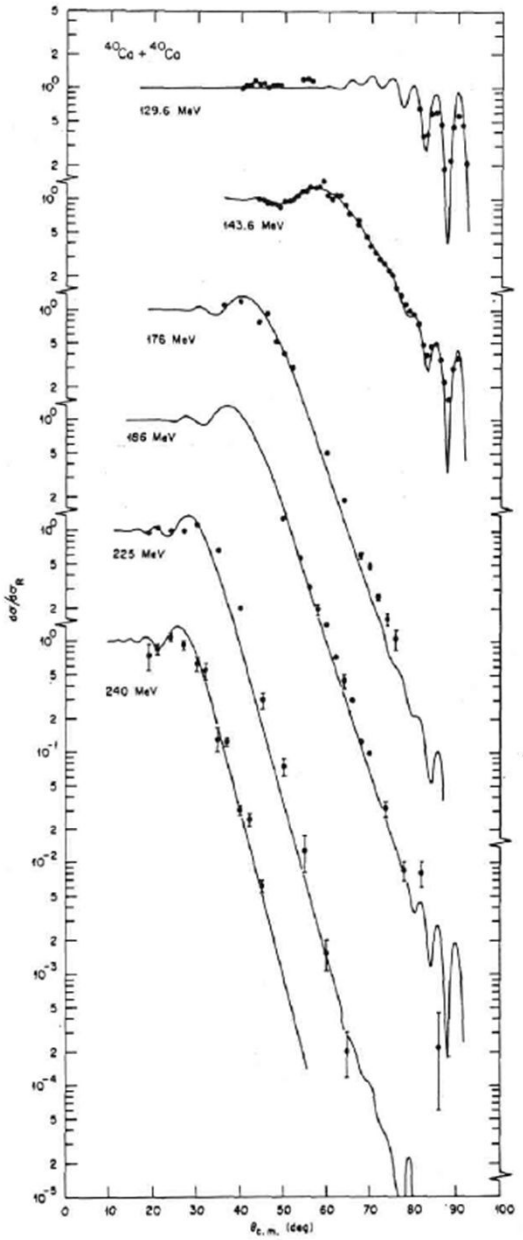
Physics Reports 55('79) 183









System[a)]	E_{Lab} (MeV)	N	W (MeV)
$^{10}B+^{12}C$	100	*1.03*	*15.1*
$^{10}B+^{16}O$	99.4	1.04	16.5
$^{11}B+^{208}Pb$	72.2	1.26	18.8
$^{11}B+^{209}Bi$	74.6	1.45	20.7
$^{12}C+^{12}C$	70–126	1.01–1.13	10–19
$^{12}C+^{28}Si$	131.5	0.84	52.4
$^{12}C+^{40}Ca$	45	1.14	10.4
$^{12}C+^{90}Zr$	98	0.98	8.9
$^{12}C+^{142}Nd$	70.4	1.15	15.8
$^{12}C+^{208}Pb$	96	1.25	16.0
$^{12}C+^{208}Pb$	116.4	1.26	14.7
$^{13}C+^{207}Pb$	86.1	1.27	31.6
$^{14}N+^{12}C$	156.5	1.03	15.1
$^{14}N+^{16}O$	154.3	1.30	18.3
$^{15}N+^{89}Y$	49.5	1.18	15.1
$^{16}O+^{12}C$	168	1.11	18.0
$^{16}O+^{28}Si$	37.7	1.01	7.5
$^{16}O+^{28}Si$	53	1.00	8.5
$^{16}O+^{28}Si$	60	1.01	8.5
$^{16}O+^{28}Si$	66	1.01	7.3
$^{16}O+^{28}Si$	72	1.00	9.1
$^{16}O+^{28}Si$	81	1.00	8.6
$^{16}O+^{28}Si$	141.5	0.91	74.3
$^{16}O+^{28}Si$	215.2	0.76	79.0
$^{16}O+^{40}Ca$	40	*1.14*	*12.9*
$^{16}O+^{40}Ca$	55.6	1.27	12.9
$^{16}O+^{40}Ca$	60	1.26	13.3
$^{16}O+^{40}Ca$	74.4	1.14	12.9
$^{16}O+^{40}Ca$	103.6	0.99	13.2
$^{16}O+^{40}Ca$	139.6	1.23	14.7
$^{16}O+^{40}Ca$	214.1	1.05	13.8
$^{16}O+^{48}Ca$	40	*0.98*	*13.3*
$^{16}O+^{48}Ca$	56	0.98	13.3
$^{16}O+^{59}Co$	40	0.98	12.4
$^{16}O+^{59}Co$	45.5	0.87	11.1
$^{16}O+^{59}Co$	49	1.10	10.3
$^{16}O+^{59}Co$	52	0.99	12.0
$^{16}O+^{59}Co$	56	1.00	12.2
$^{16}O+^{59}Co$	141.7	1.00	11.7

System[a)]	E_{Lab} (MeV)	N	W (MeV)
$^{16}O+^{60}Ni$	61.4	1.04	10.8
$^{16}O+^{60}Ni$	141.7	1.00	10.7
$^{16}O+^{88}Sr$	48	1.36	10.4
$^{16}O+^{88}Sr$	52	1.19	11.6
$^{16}O+^{88}Sr$	56	1.21	19.8
$^{16}O+^{88}Sr$	59	1.22	23.6
$^{16}O+^{208}Pb$	129.5	1.16	19.4
$^{16}O+^{208}Pb$	192	0.95	15.6
$^{16}O+^{208}Pb$	312.6	1.05	11.4
$^{17}O+^{40}Ca$	61.07	1.10	13.9
$^{32}S+^{27}Al$	100	1.08	24.5
$^{32}S+^{32}S$	90.88	1.22	22.7
$^{32}S+^{40}Ca$	100	1.26	24.4
$^{32}S+^{48}Ca$	83.3	1.09	58.7
$^{40}Ca+^{40}Ca$	143.6	1.32	14.7
$^{40}Ca+^{40}Ca$	129.6	*1.32*	*14.7*
$^{40}Ca+^{40}Ca$	176.0	*1.32*	*14.7*
$^{40}Ca+^{40}Ca$	186.0	*1.32*	*14.7*
$^{40}Ca+^{40}Ca$	225	*1.32*	*14.7*
$^{40}Ca+^{40}Ca$	240	*1.32*	*14.7*

Love & Satchler ,

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System	E_{Lab} (MeV)	N	W (MeV)
^{6}Li Scattering			
$^{6}Li+^{28}Si$	135.1	0.62	43.5
$^{6}Li+^{40}Ca$	28	0.62	9.8
$^{6}Li+^{40}Ca$	30	0.60	9.5
$^{6}Li+^{40}Ca$	34	0.60	10.2
$^{6}Li+^{40}Ca$	50.6	0.63	11.3
$^{6}Li+^{40}Ca$	156	0.66	30.6
$^{6}Li+^{44}Ca$	30	0.55	11.2
$^{6}Li+^{48}Ca$	28	0.65	11.5
$^{6}Li+^{48}Ca$	34	0.60	9.6
$^{6}Li+^{58}Ni$	22.8	0.37	11.1
$^{6}Li+^{58}Ni$	50.6	0.60	11.9
$^{6}Li+^{90}Zr$	34	0.79	11.8
$^{6}Li+^{90}Zr$	73.7	0.58	13.4
$^{6}Li+^{90}Zr$	156	0.63	27.1
$^{6}Li+^{124}Sn$	50.6	0.78	12.3
$^{6}Li+^{208}Pb$	50.6	0.59	11.8

^{9}Be scattering

Target	E_{lab} (MeV)	N	W (MeV)
^{28}Si	12		
	14		
	17		
	20	0.42	9.7
	23		
	26		
	30		
	50 ± 1	0.43	12.5
	121	0.55	20.9
	201.6	0.49	22.2
^{40}Ca	14		
	20	0.34	12.3
	26		
^{58}Ni	20		
	26	0.62	13.3
^{208}Pb	50 ± 1	0.36	14.0

○ ^{6}Li散乱偏極量における分解状態の寄与と模型空間に対する収束性

CDCC

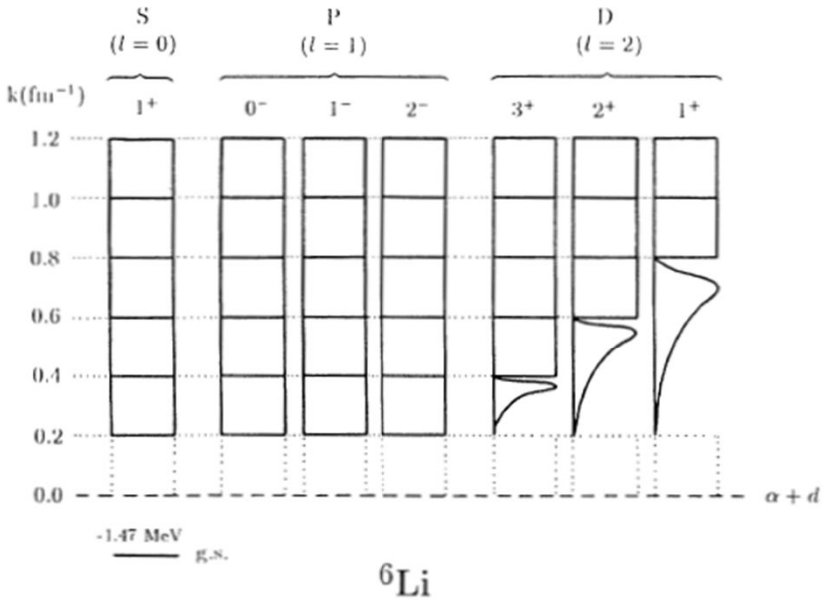
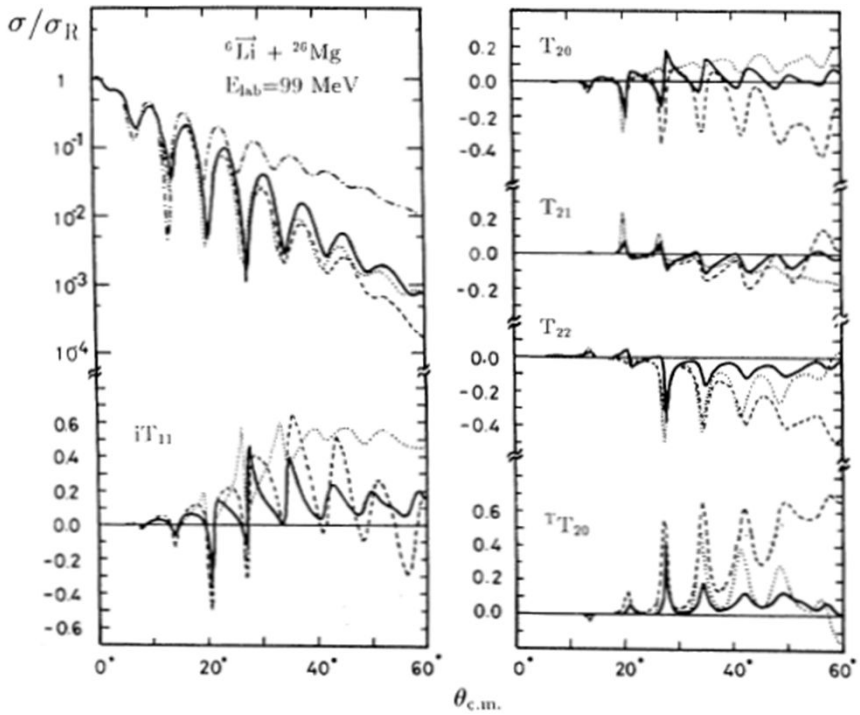


FIG. 3. The full model space of ^{6}Li→$\alpha+d$ breakup states resulting from the tests of convergence.

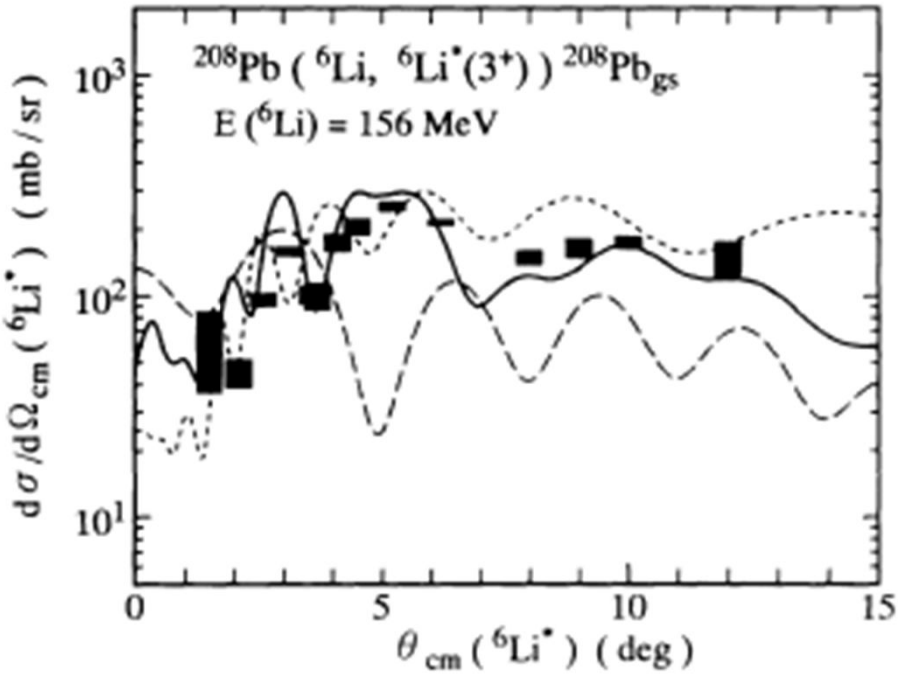


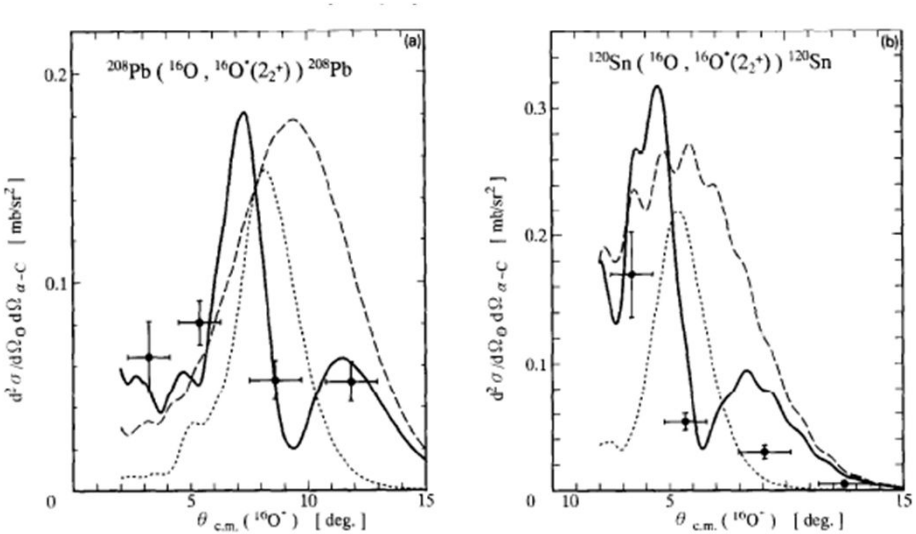
Y.H., PRC44('91) 1581

○ Astrophysical Interest（Coulomb breakup or Nuclear Breakup ?）

CDCC, MCC

Y.H., Sakuragi, PRL69('92) 1892





O'Kelly et.al.(Y.H,), PLB393('97) 301

- Nuclear/Coulomb breakup の定量的記述の成功
- 強い Nuclear breakup （超前方でさえ）

  → Coulomb breakup シナリオの破綻

○ $^{24}Mg = {}^{12}C^* + {}^{12}C^*$ 高励起状態の構造　　Microscopic CC

68, NUMBER 9　　PHYSICAL REVIEW LETTERS　　2 M

Evidence for Alpha-Particle Chain Configurations in ^{24}Mg

A. H. Wuosmaa, R. R. Betts, B. B. Back, M. Freer, B. G. Glagola, Th. Happ, D. J. Henderson, and P. Wilt
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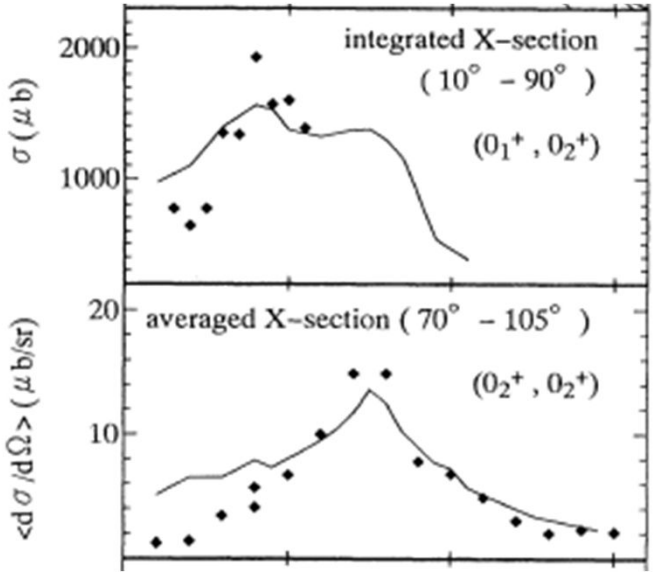
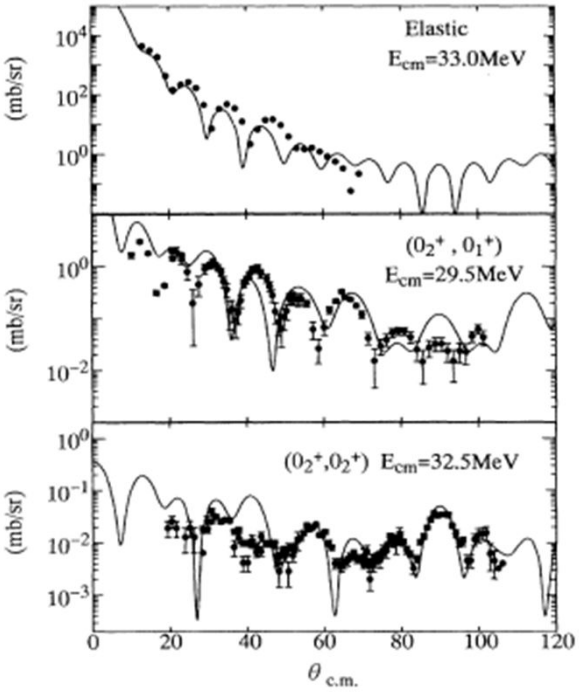
$^{24}Mg = {}^{12}C(0_2^+) + {}^{12}C(0_2^+)$, Ecm=32.5MeV の共鳴は 6 α 鎖状構造か？

$^{12}C\,(\,{}^{12}C,\,{}^{12}C(0_2^+)\,)\,{}^{12}C(0_2^+)$　　Y.H., Sakuragi, Abe, PRL74('95) 4141

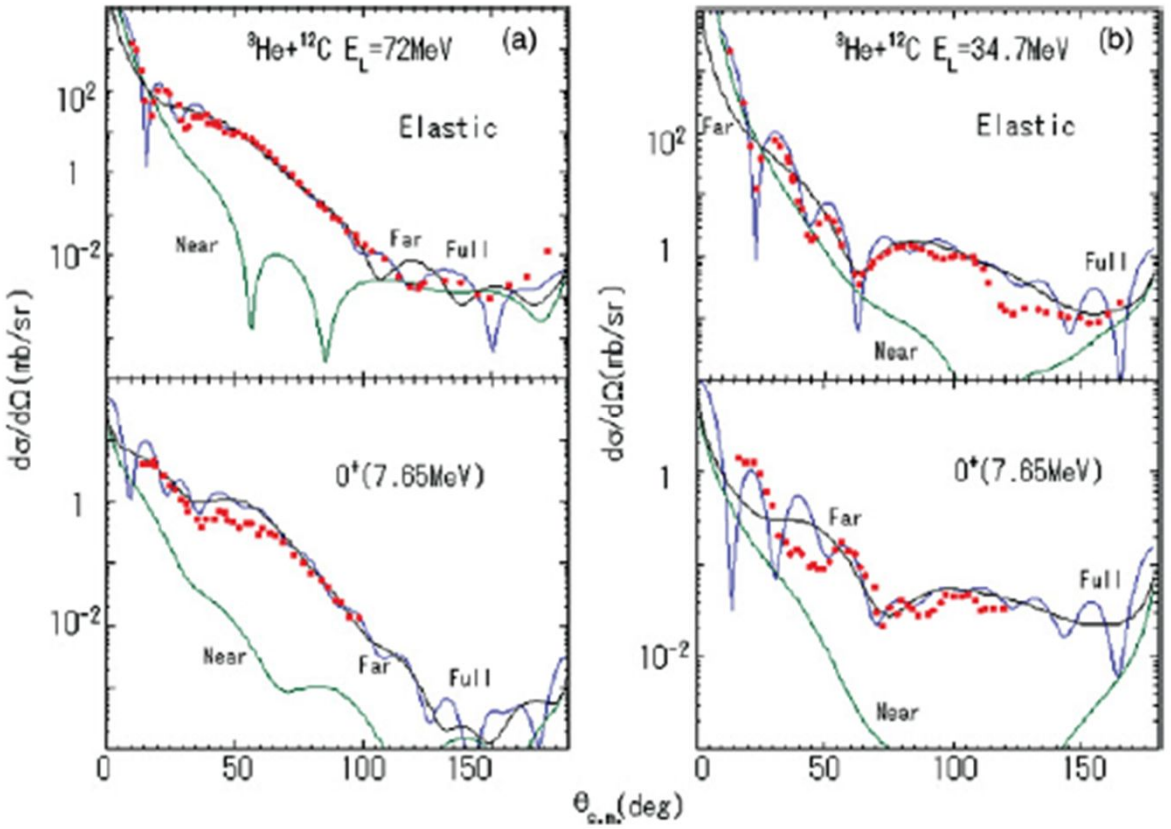




→ 2 つの $^{12}C(0_2^+) = 3\alpha$ （非鎖状）の弱結合状態

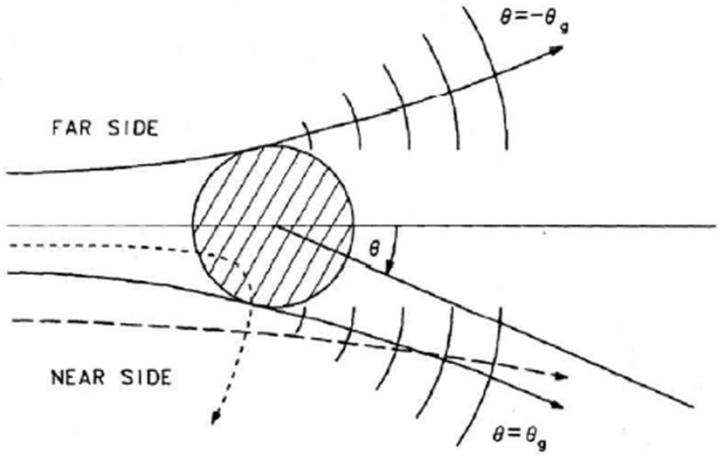
○ $^{12}C(0_2^+)$ Hoyle state（α凝縮状態？）と核虹　　MCC

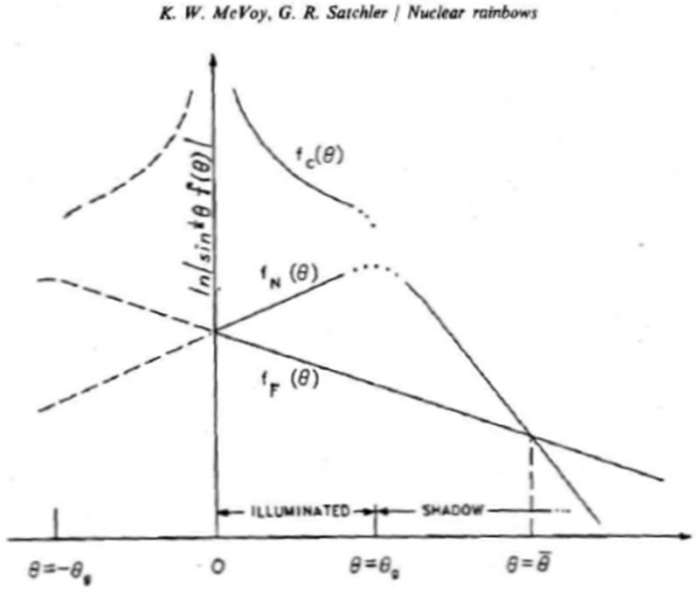
Ohkubo, Y.H., PRC75 ('07) 3044609



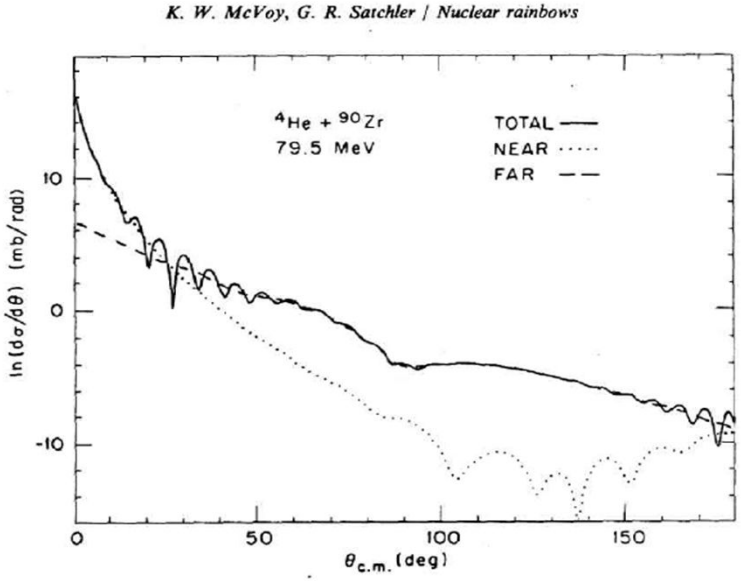
- 核虹の存在
- 弾性散乱とHoyle stateにおける位置（角度）の違い

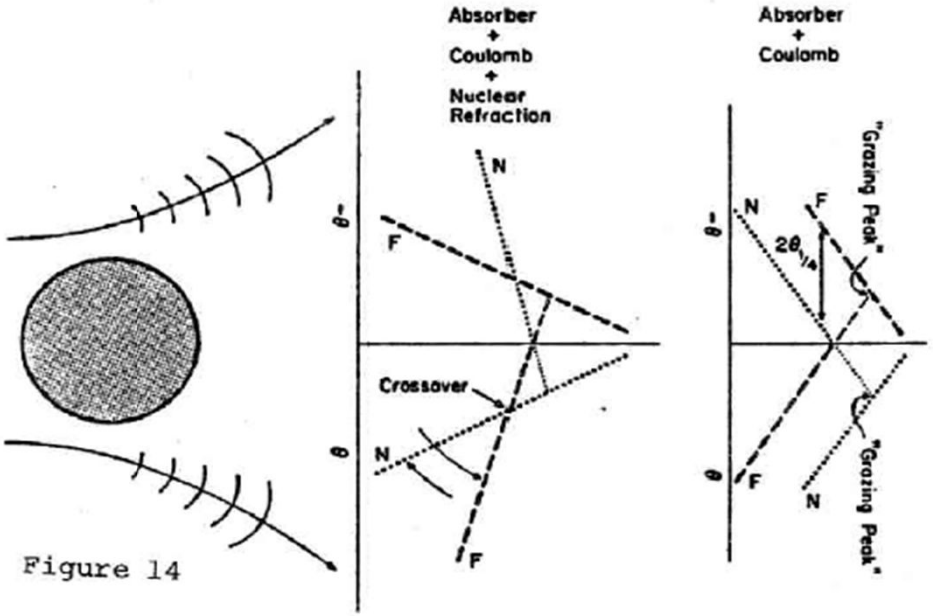
◆ Near/Far decomposition





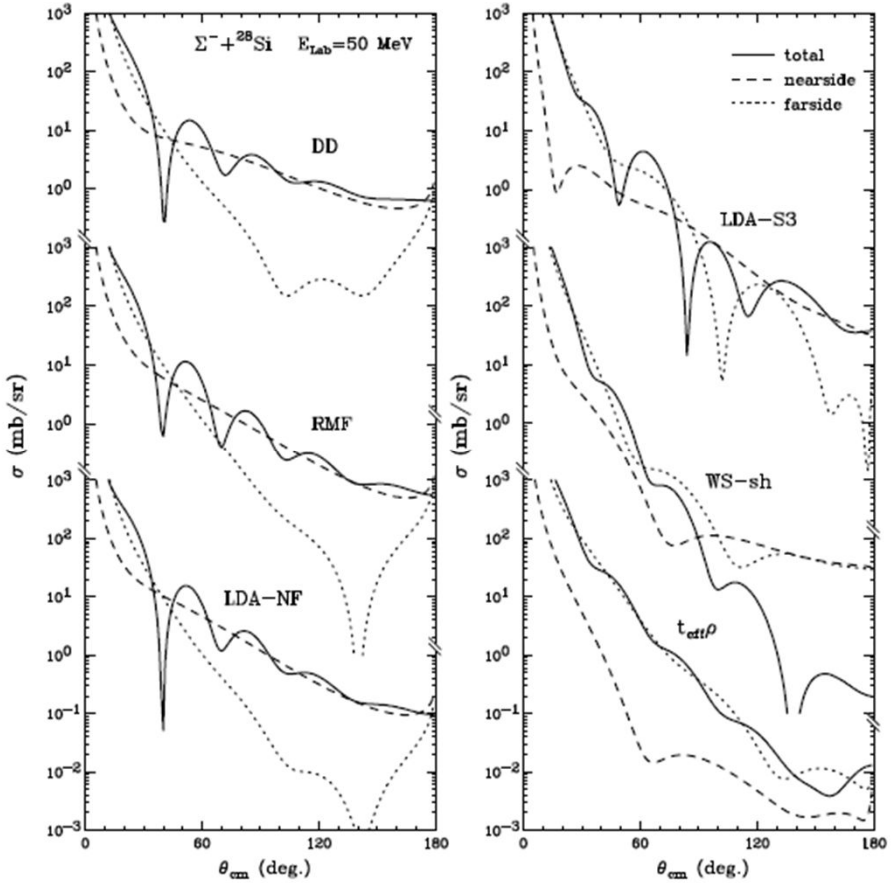
McVOY & Satchler, NPA417('84) 157

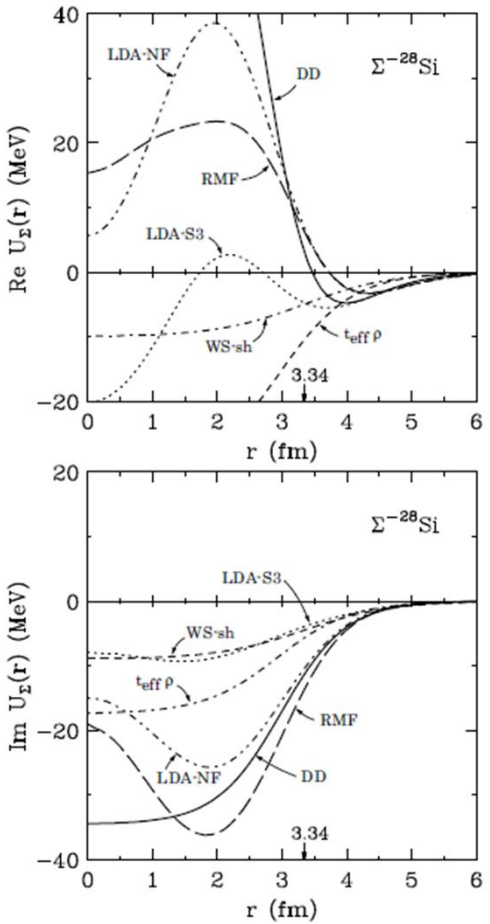




McVOY , Lecture Note of 1983 RCNP KIKUCHI Summer School

○ Σ^- + 原子核散乱微分断面積　　potential scattering (single channel)





- Near/Far 逆転（⇔原子核+原子核散乱）
- 十分な斥力ポテンシャル
- 斥力部分と引力部分（Coulomb含む）の競合による角分布

○ ^{3}He (K^{-}, $\pi^{-/+}$) reactions

$$ {}^{3}_{Y}\mathrm{He} = (NN)Y + (NN)^{*}Y $$

CDCC