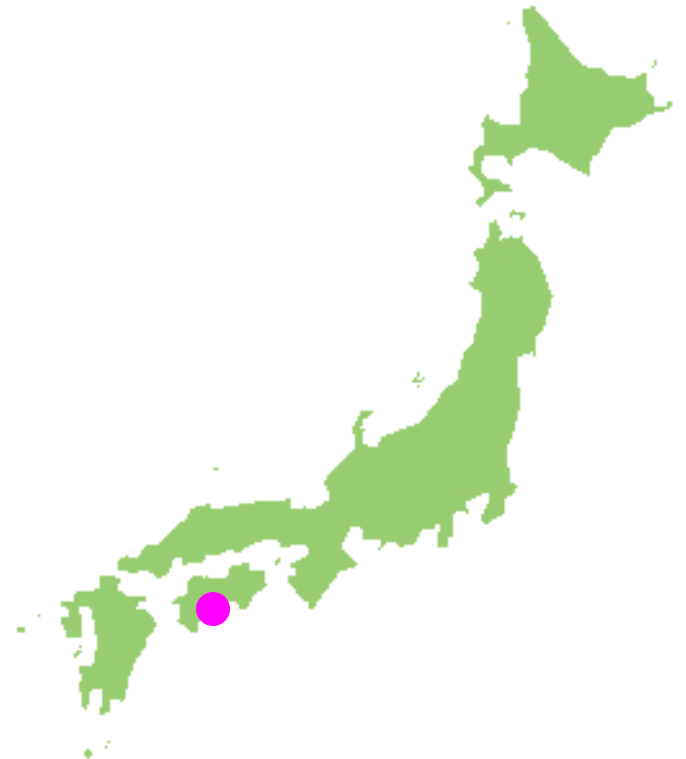


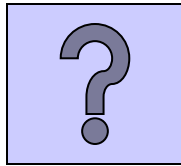
原子核の虹散乱と核構造

大久保茂男 S. Ohkubo
(高知県立大・環境理学科)
Univ. of Kochi



講演の概要

- ニュートンの虹と原子核の虹(核虹、湯川虹)
- クラスタ構造: トラップされた虹
- 核虹とプレインボウ 高次エアリー構造
- 非弾性核虹、フラジャイル核での核虹が観測
- α 粒子のボーズ・アインシュタイン凝縮と核虹



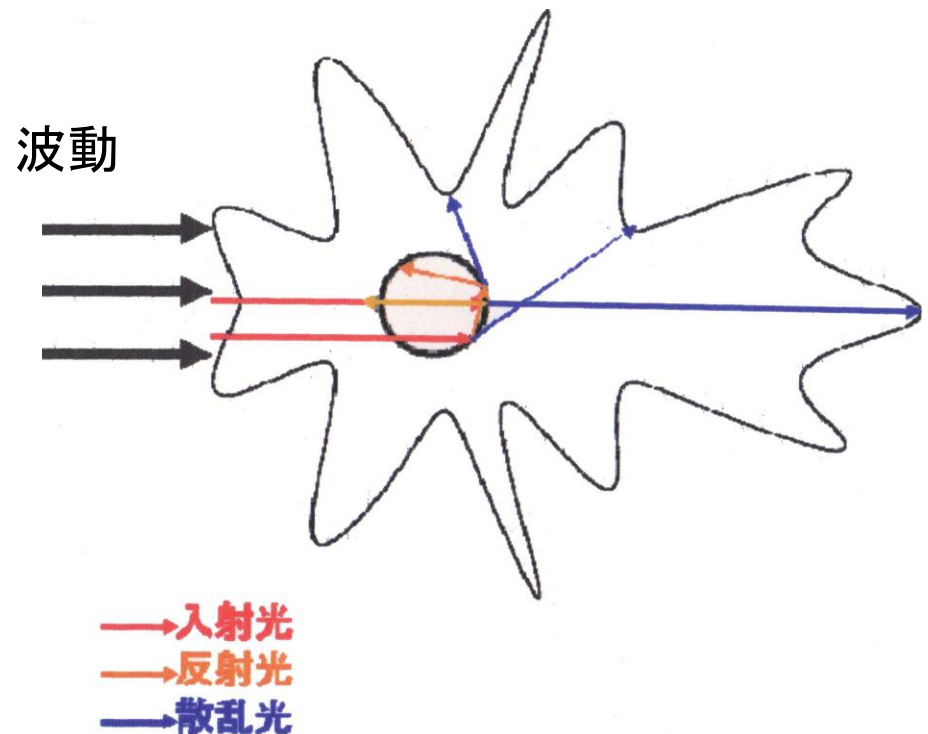
Mie散乱

虹現象はMie散乱によって説明できる

Mie散乱とは光の波長より大きな物質に光がぶつかったときの散乱.

光の波長依存性がなく、すべての波長が散乱される.

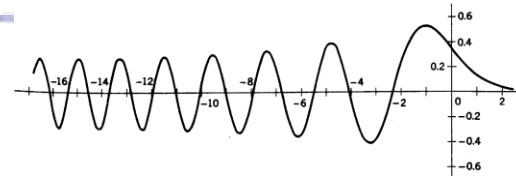
例: 雲が白くみえる.



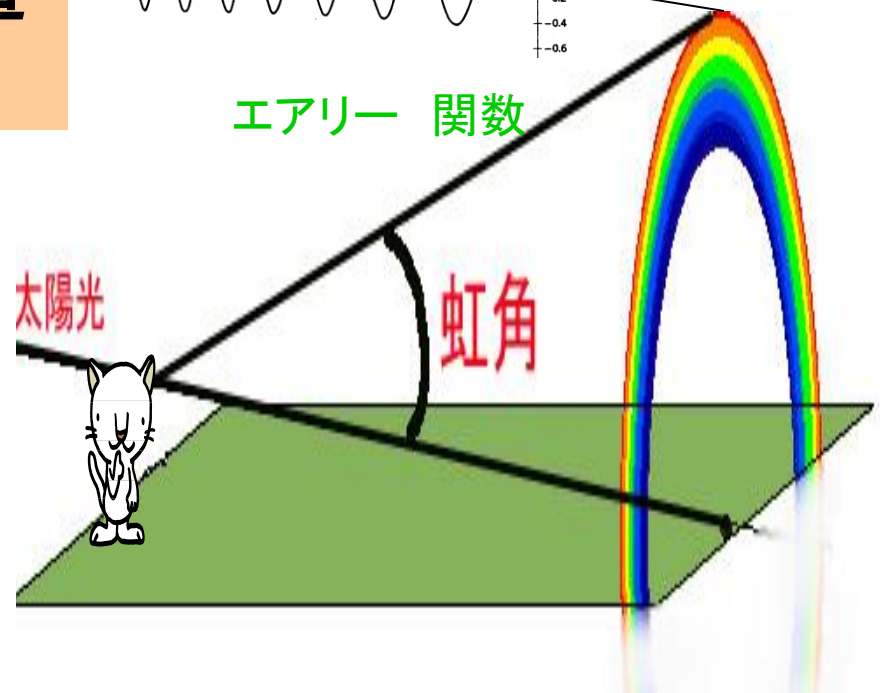
水滴半径1.6mm散乱強度分布

散乱振幅のDebye展開

エアリー構造
(過剰虹)

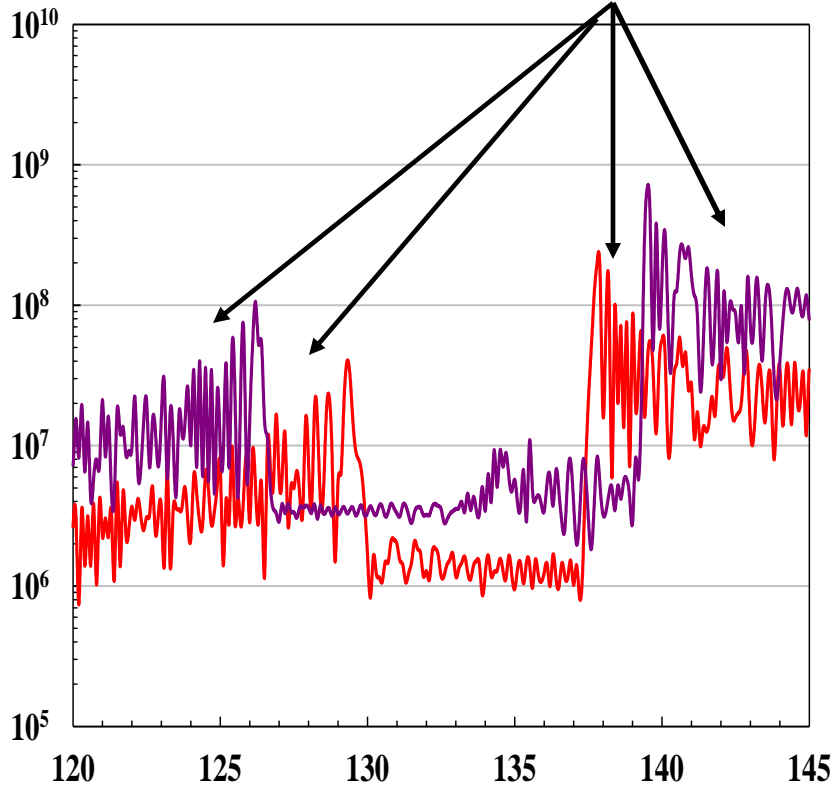


エアリー関数



虹角 = $180^\circ - \text{散乱角}(\theta)$
 $0 < \theta < 90$ 見えない
 $90 < \theta < 180$ 見える

ニュートンのp次の虹



散乱光強度

散乱角(度)

2011 Aug 2

核反戻

水滴の大きさと散乱強度

赤 (波長 $0.65\mu\text{m}$)

エアリー
構造

副虹

主虹

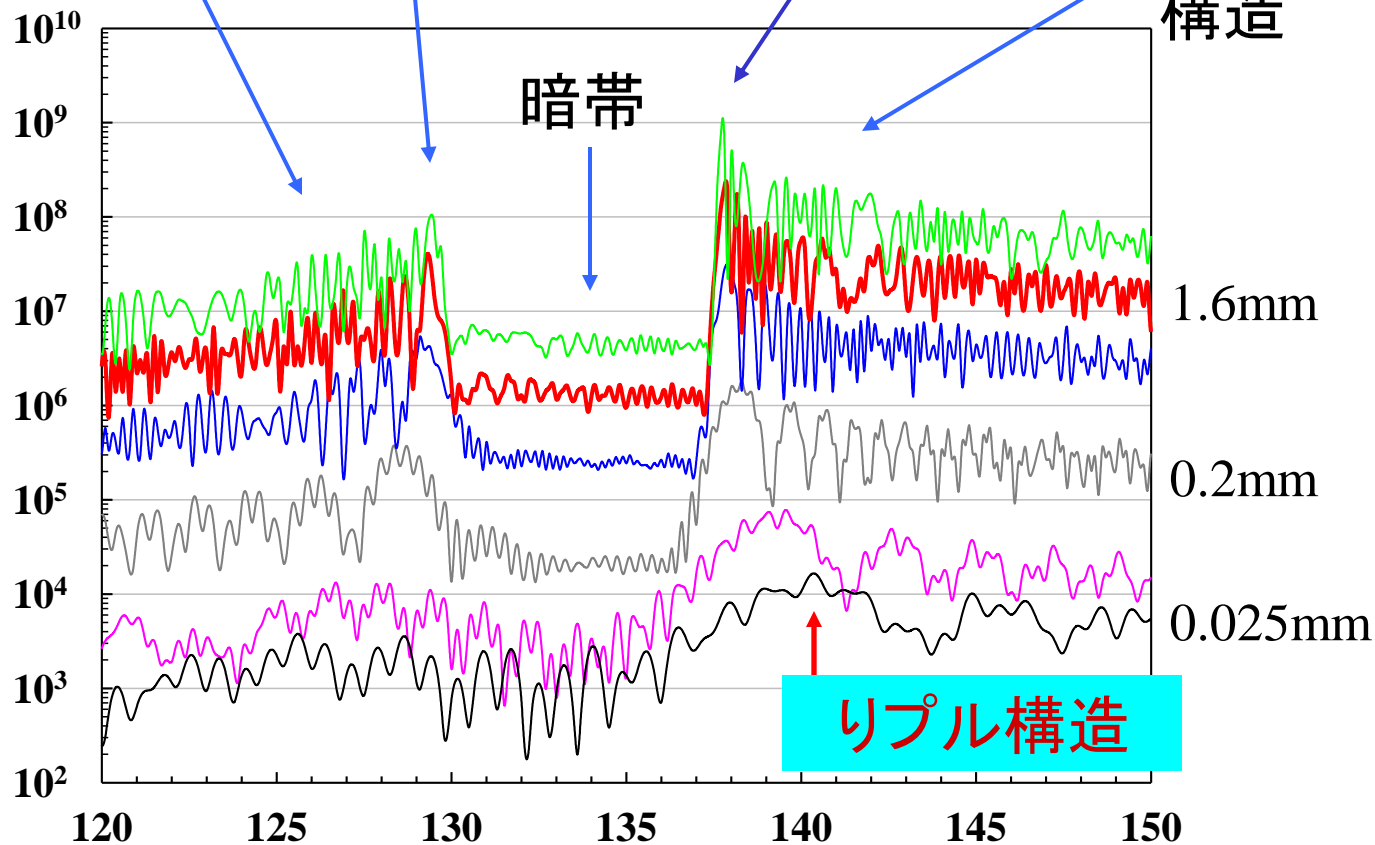
エアリー
構造

大

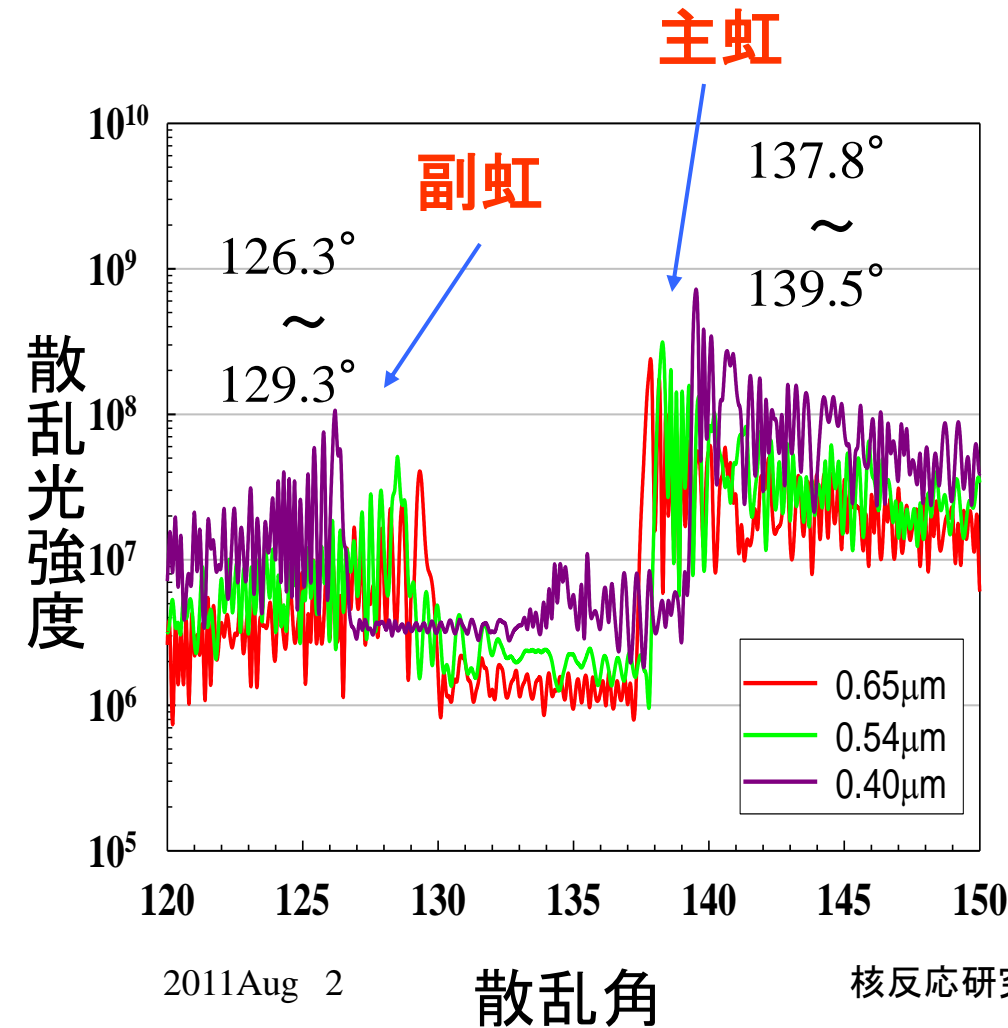
水滴の半径

小

散乱光強度

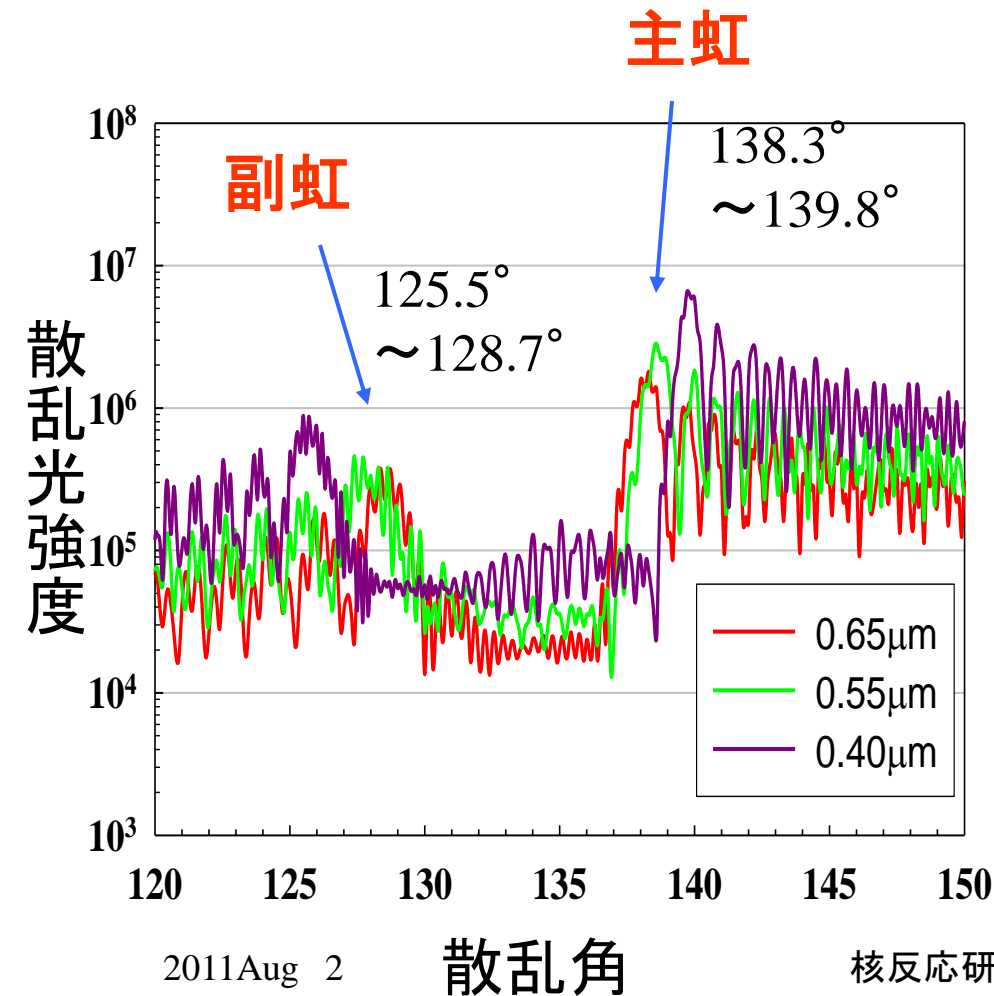


水滴 半径1.6mm



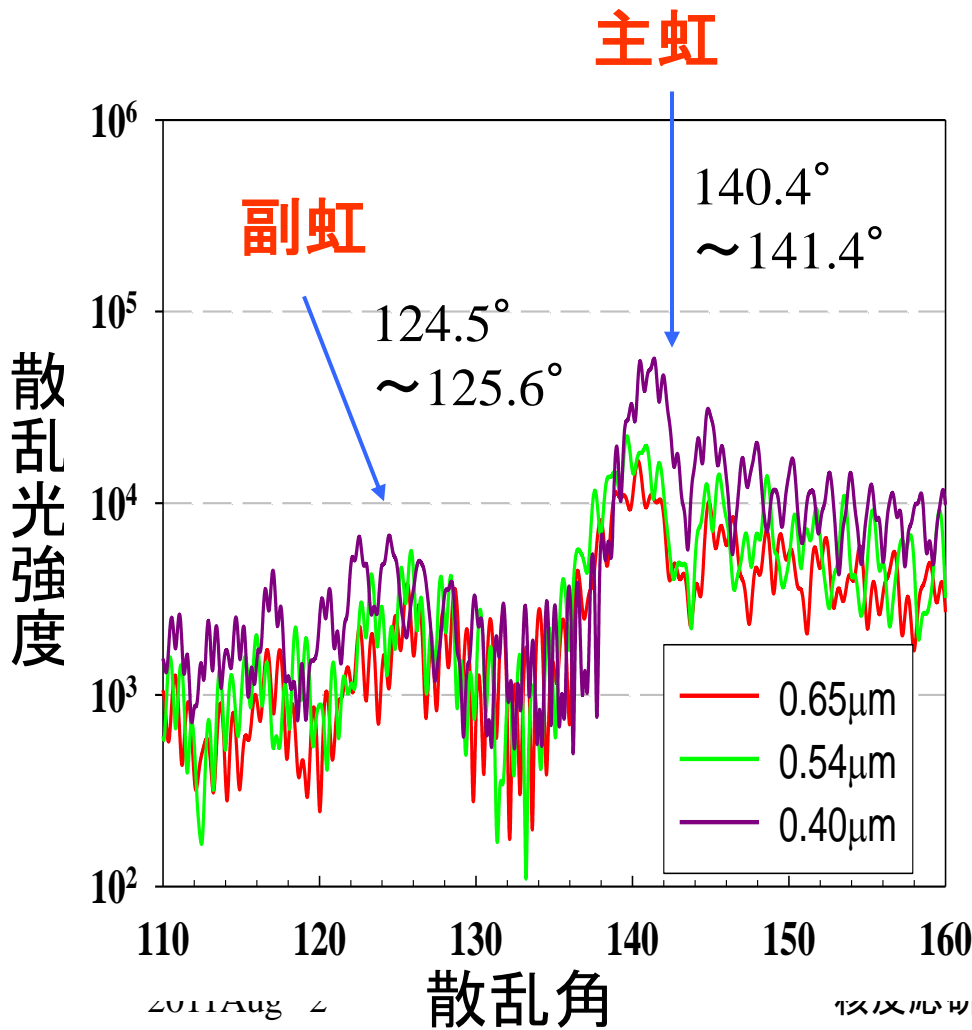
自然虹

水滴 半径0.2mm



自然虹

水滴 半径0.025mm

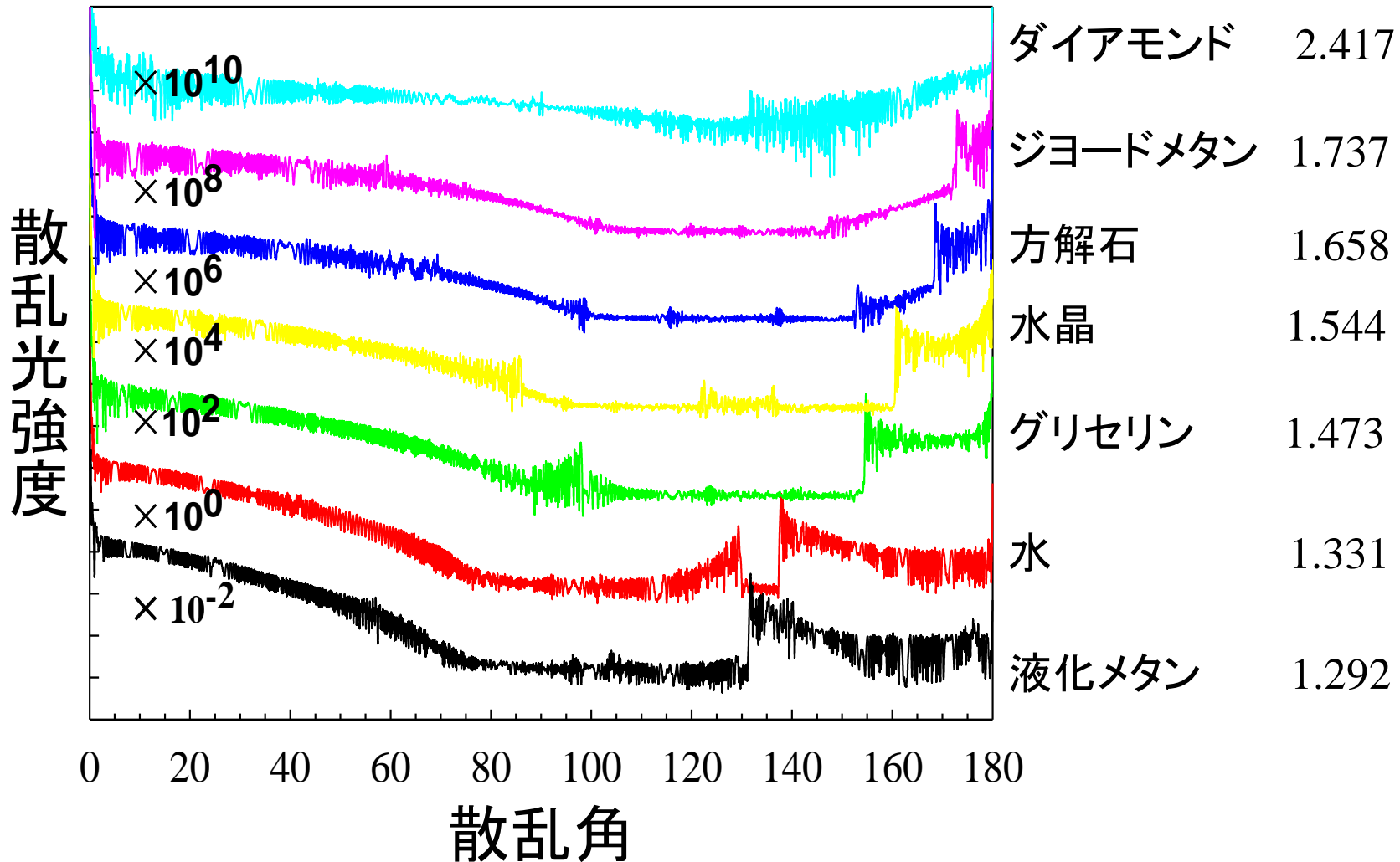


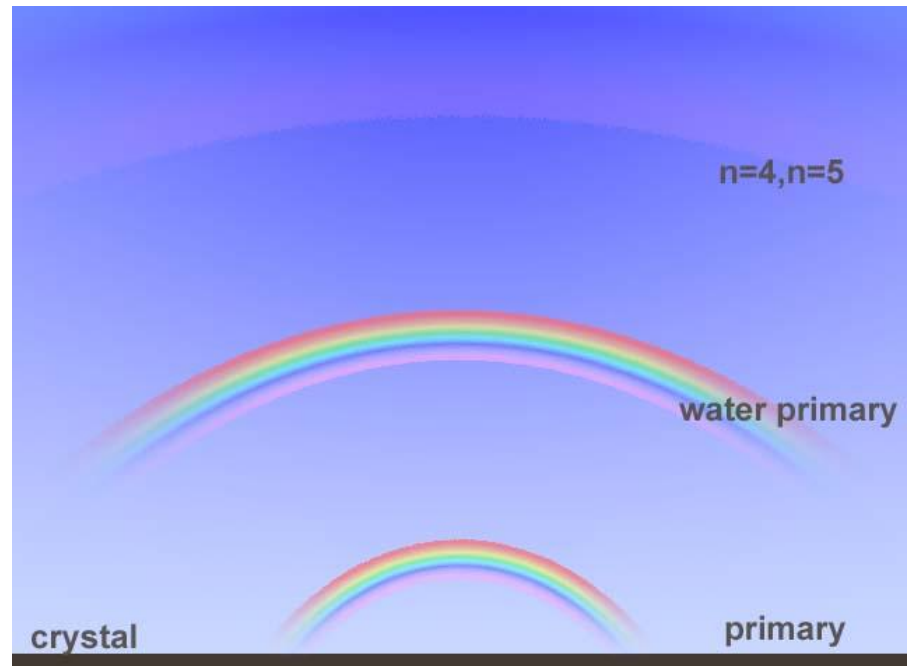
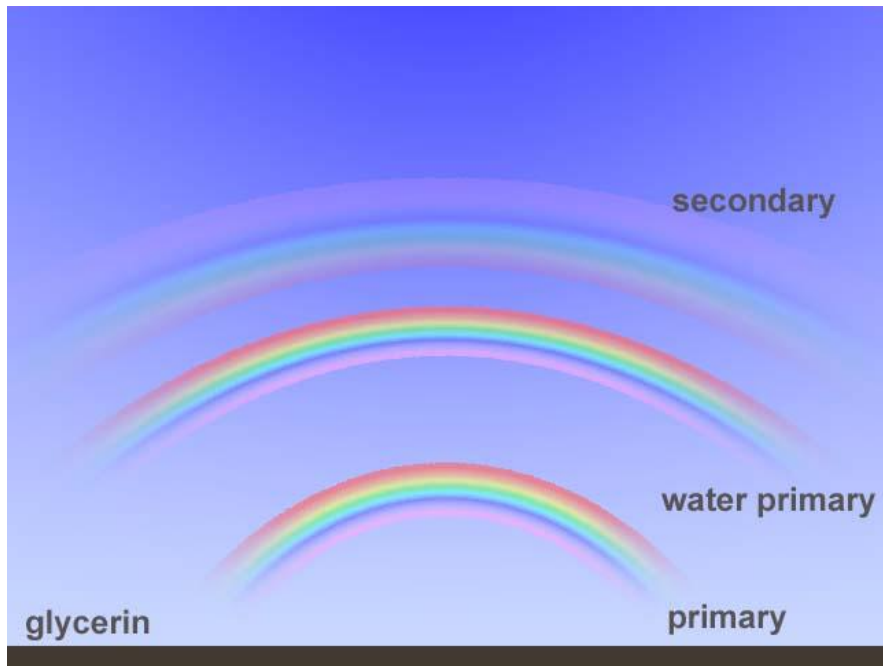
自然虹

屈折率が変わると……

赤 (波長 $0.589\mu\text{m}$)

物質は固有の虹構造をもつ



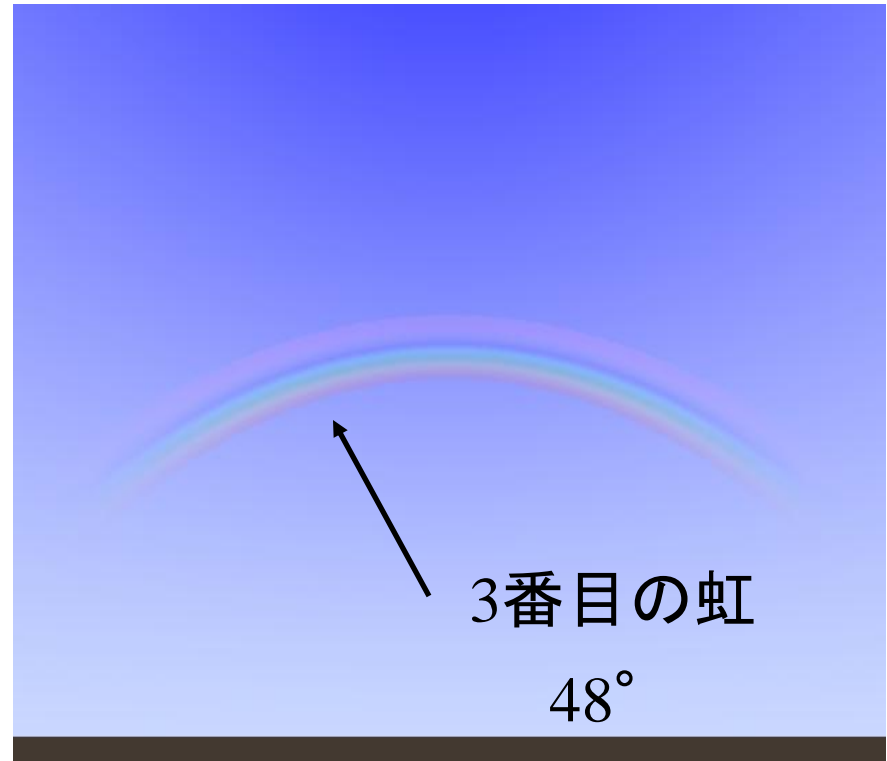
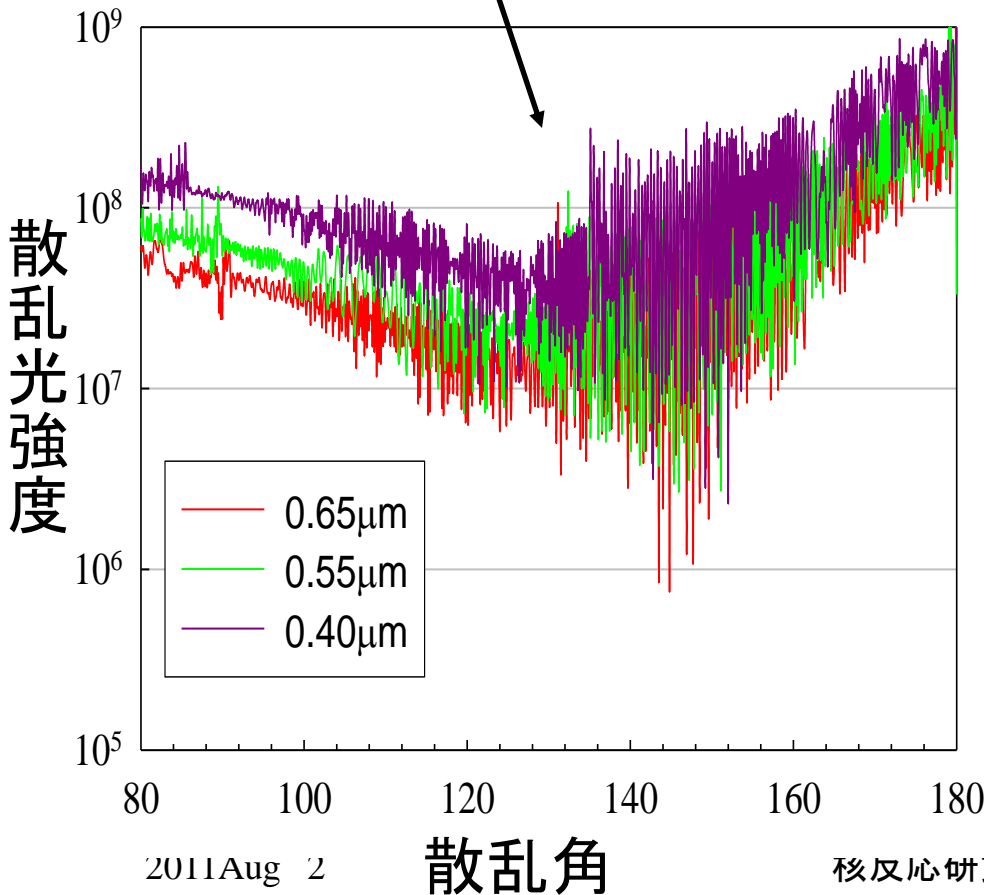


ダイヤモンド 半径1.6mm

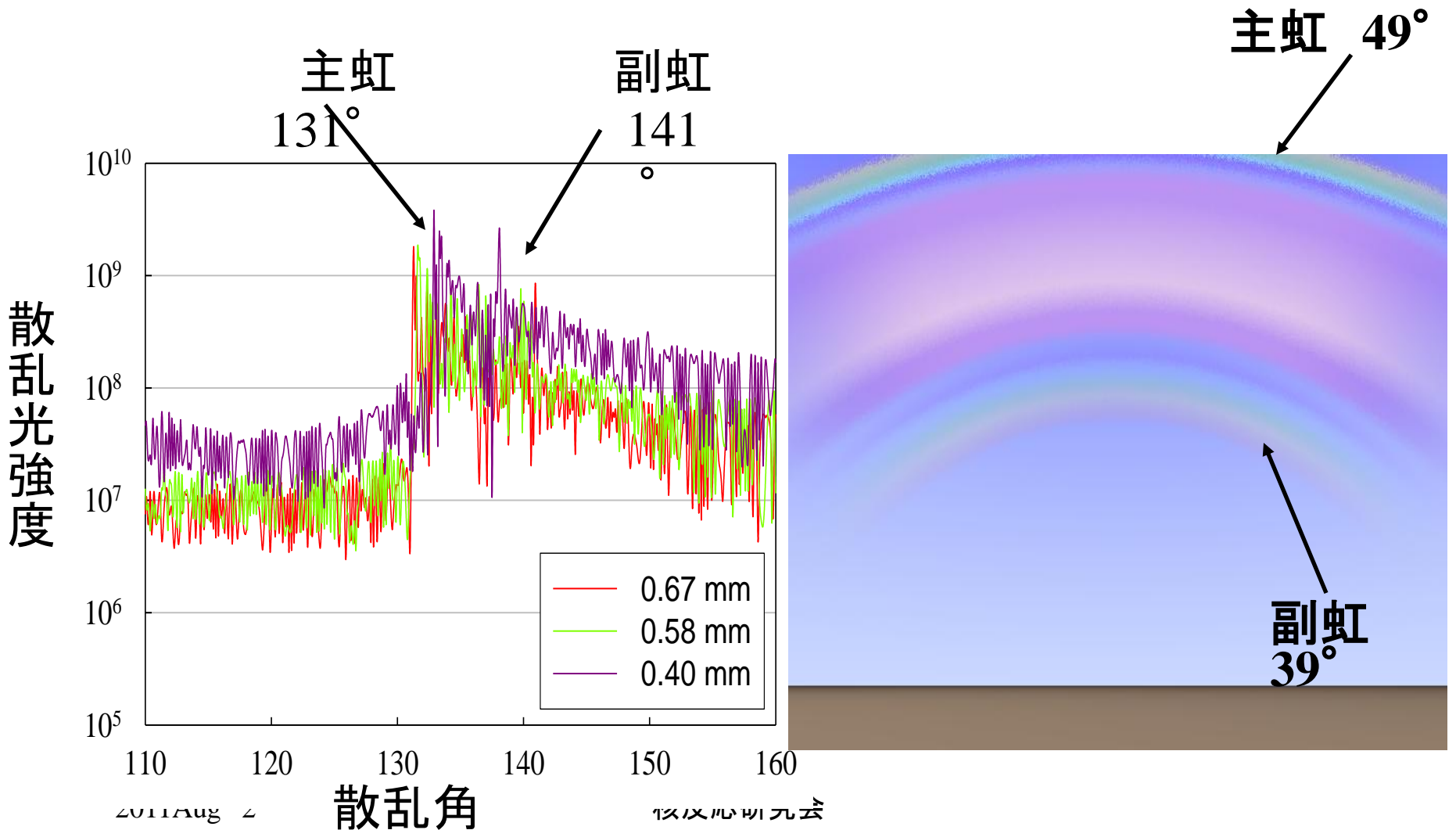
(屈折率 2.410)

3番目の虹

132°

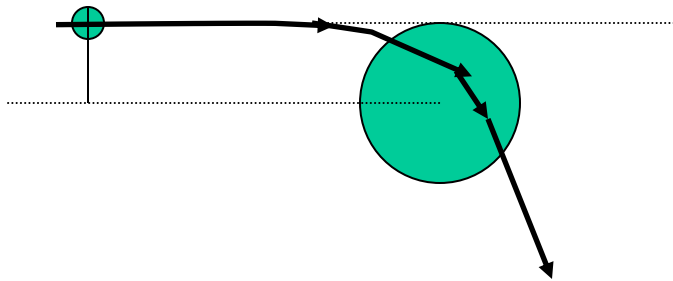


液化メタン 半径1.6mm (屈折率 1.290)

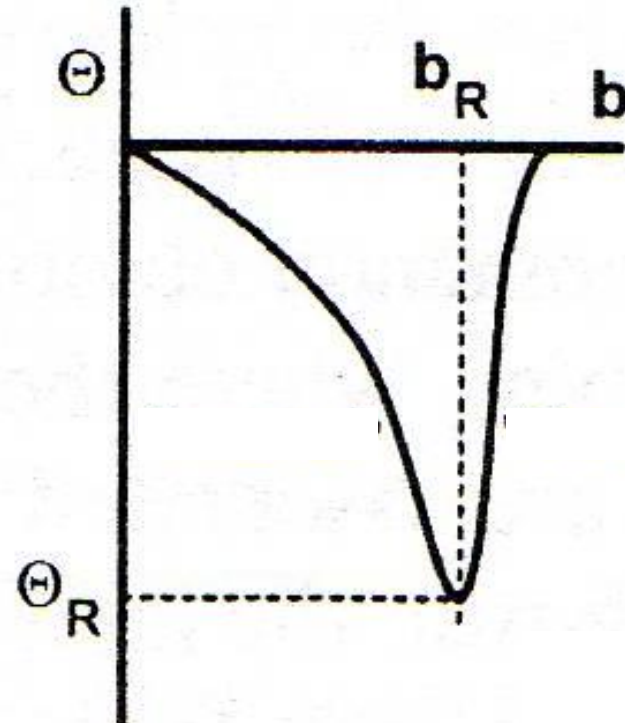


原子核の虹

α 粒子散乱により1974年Goldbergらにより実験的に発見された。



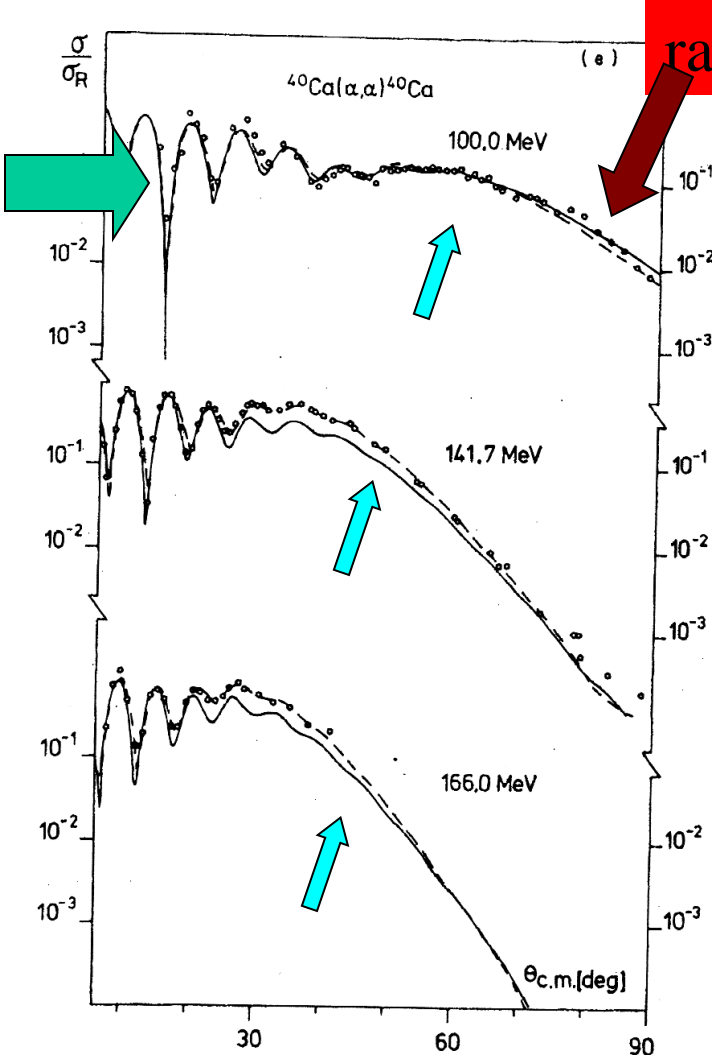
ニュートンの0次の虹



$$n = \sqrt{1 - \frac{V}{E}}$$

$\alpha + {}^{40}\text{Ca}$ 虹散乱 (吸収がすくない系)

Unique global potential (1) rainbow



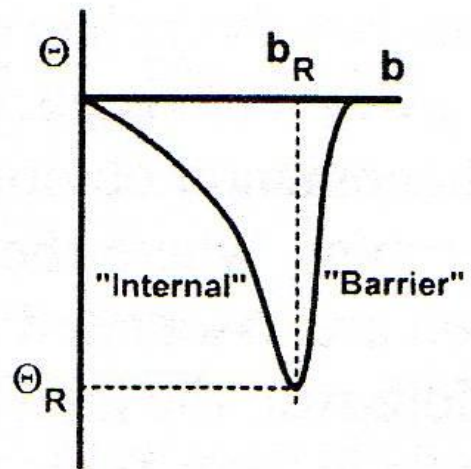
rainbow

$E = 166 \rightarrow 100 \text{ MeV}$

ポテンシャルが一意的に決まる

現象論的
Unique global $\alpha + {}^{40}\text{Ca}$ potential

$$n = \sqrt{1 - \frac{V}{E}}$$



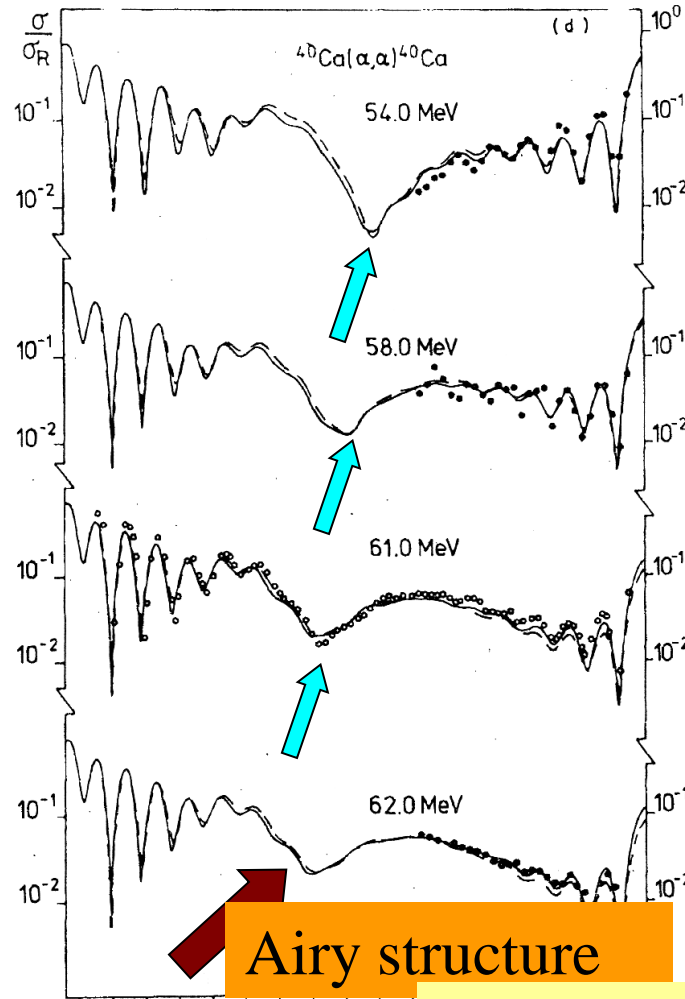
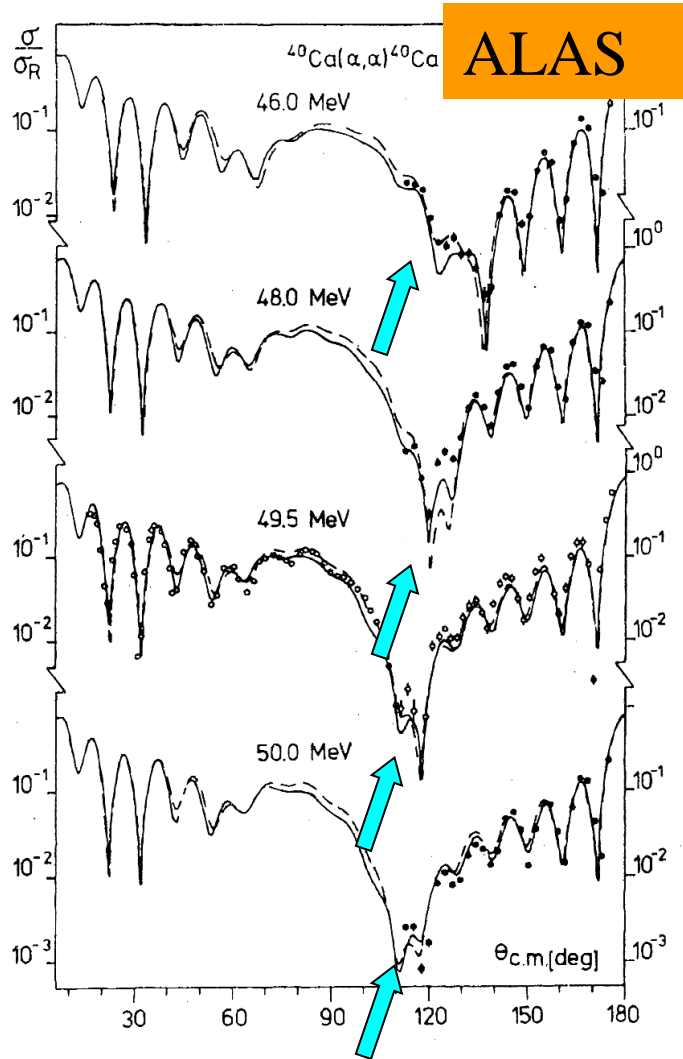
2011 Aug 2

核反応研究会

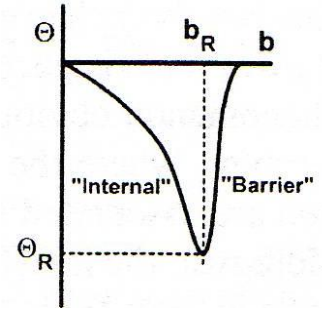
Unique global potential (2) Airy

(後方角異常)

$E=62 \rightarrow 46$ MeV

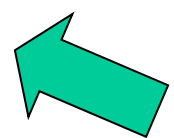


$$n = \sqrt{1 - \frac{V}{E}}$$



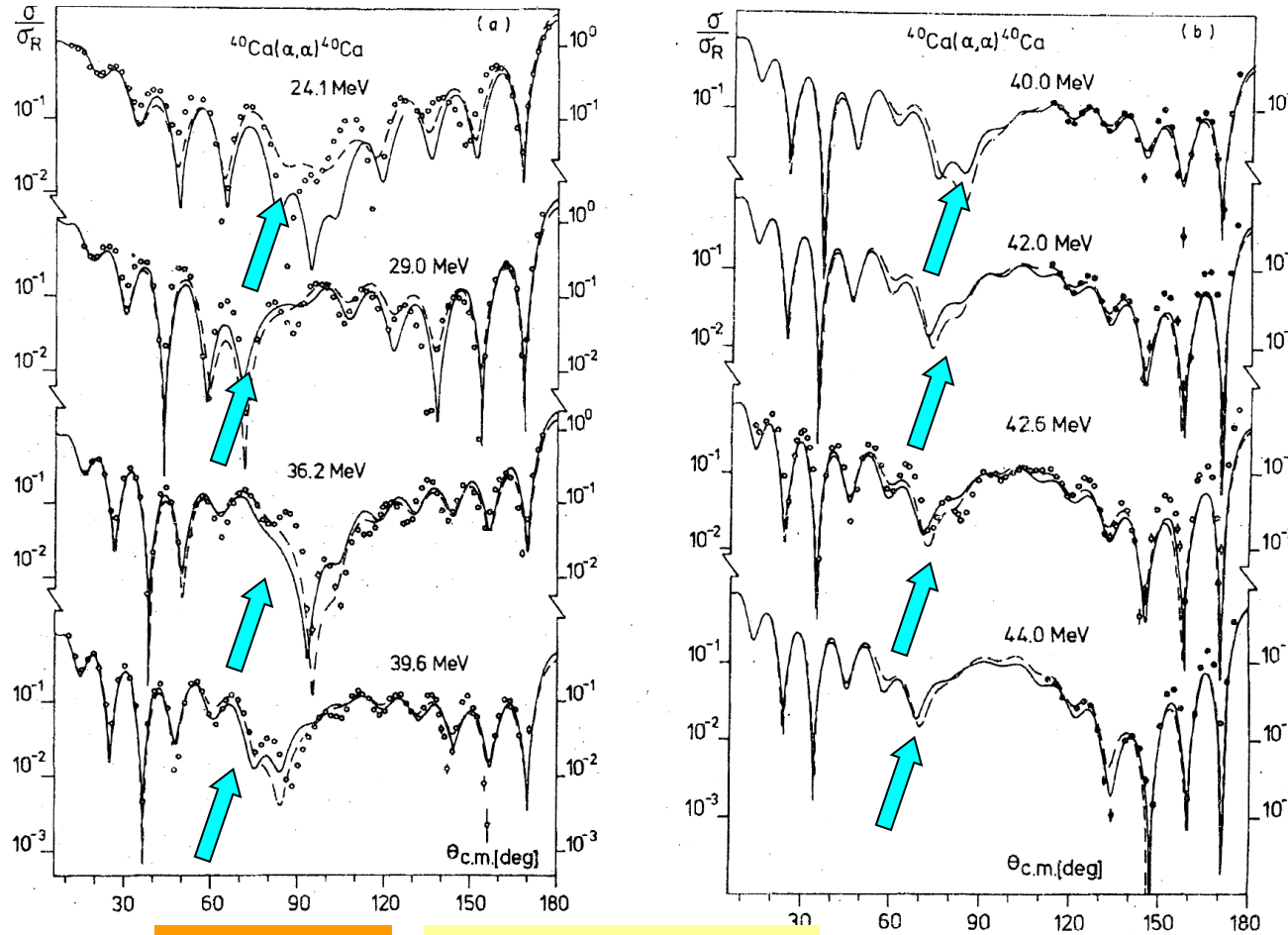
prerainbow

(エアリー構)



Unique global $\alpha + {}^{40}\text{Ca}$ potential (3) ALAS

E=44 → 24 MeV



$$n = \sqrt{1 - \frac{V}{E}}$$



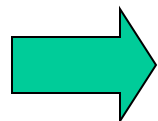
ALAS=
Overlapping
resonances

ALAS (後方角異常) Scattering
 (Anomalous Large Angle) Scattering

Unique global optical potential



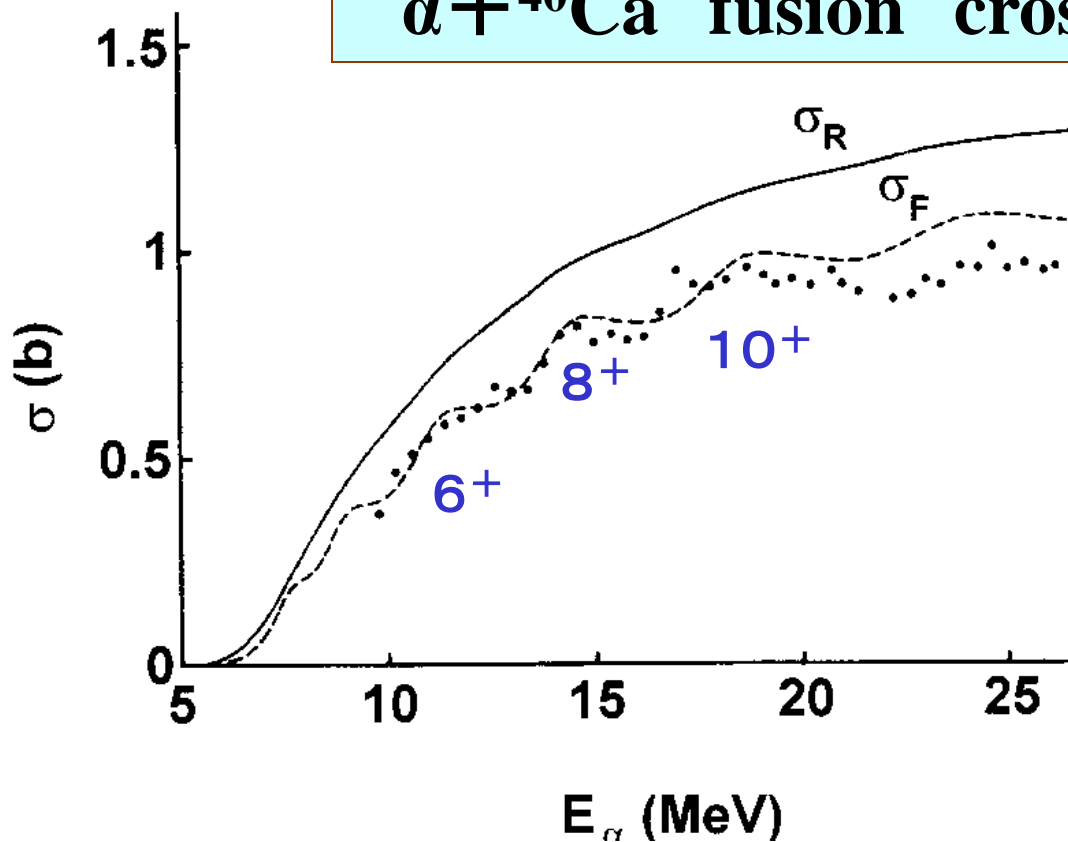
Unique global potential (4) fusion



低いエネルギー

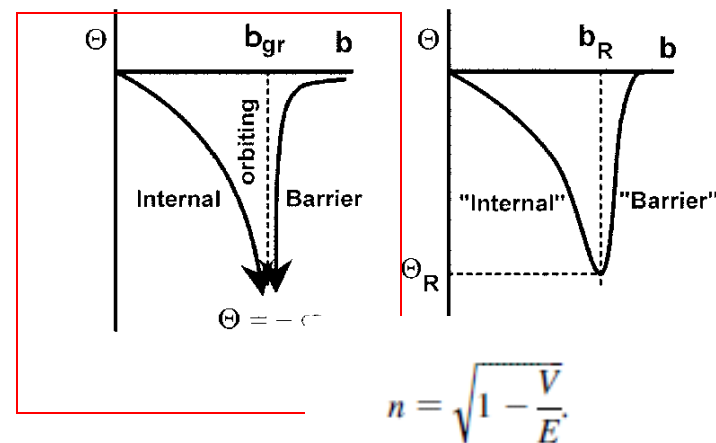
$E=25 \rightarrow 5$ MeV

$\alpha + {}^{40}\text{Ca}$ fusion cross section



鳩貝・太田・岡井の
方法で計算

PTP,68,2014,(1982)



大阪大学 RCNPでの実験 予言された $K=0^-$ バンドの発見

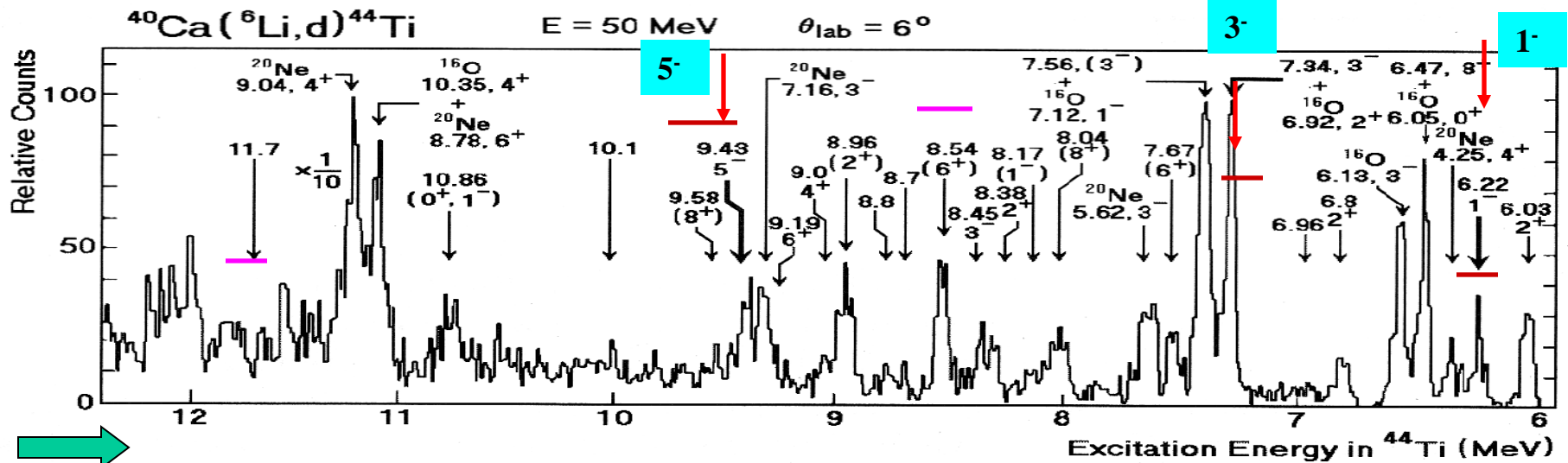
山屋堯、藤原守 他

$^{40}\text{Ca}(^6\text{Li},d)^{44}\text{Ti}$

$E = 50 \text{ MeV}$

$\theta_{\text{lab}} = 6^\circ$

Excitation Energy in ^{44}Ti (MeV)

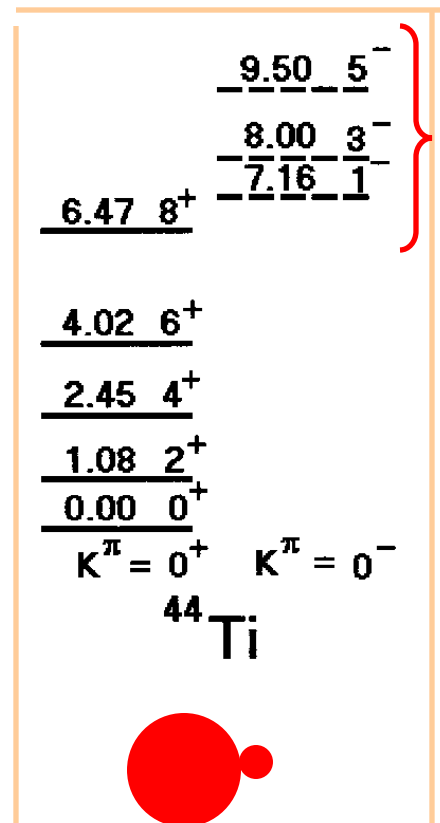
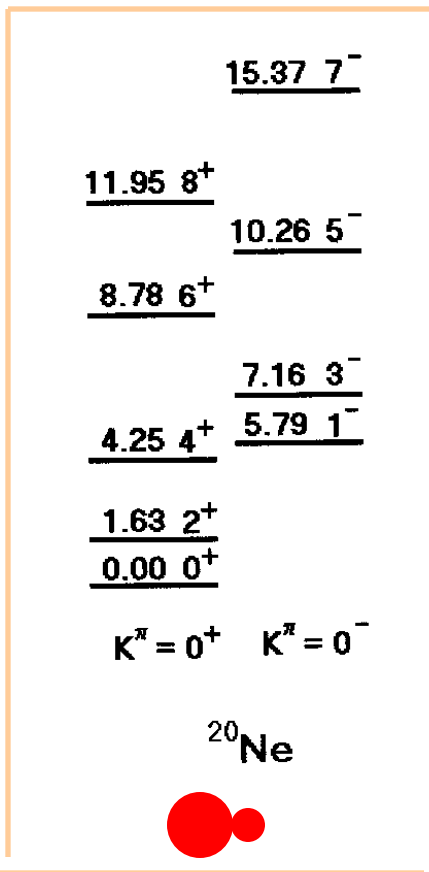


1. 11.7 MeVは強く励起されずクラスターの1でないことが判明

2. 8.54 MeVの状態は 0^+ ではない！

(いままでの実験データの方が正しくないことが判明)

RCNP ^{44}Ti $K=0^-$ 発見の実験チーム



RCNPにて ^{44}Ti の実験チーム

大久保、鹿取、山屋

2011Aug 2

(藤原守 撮影)

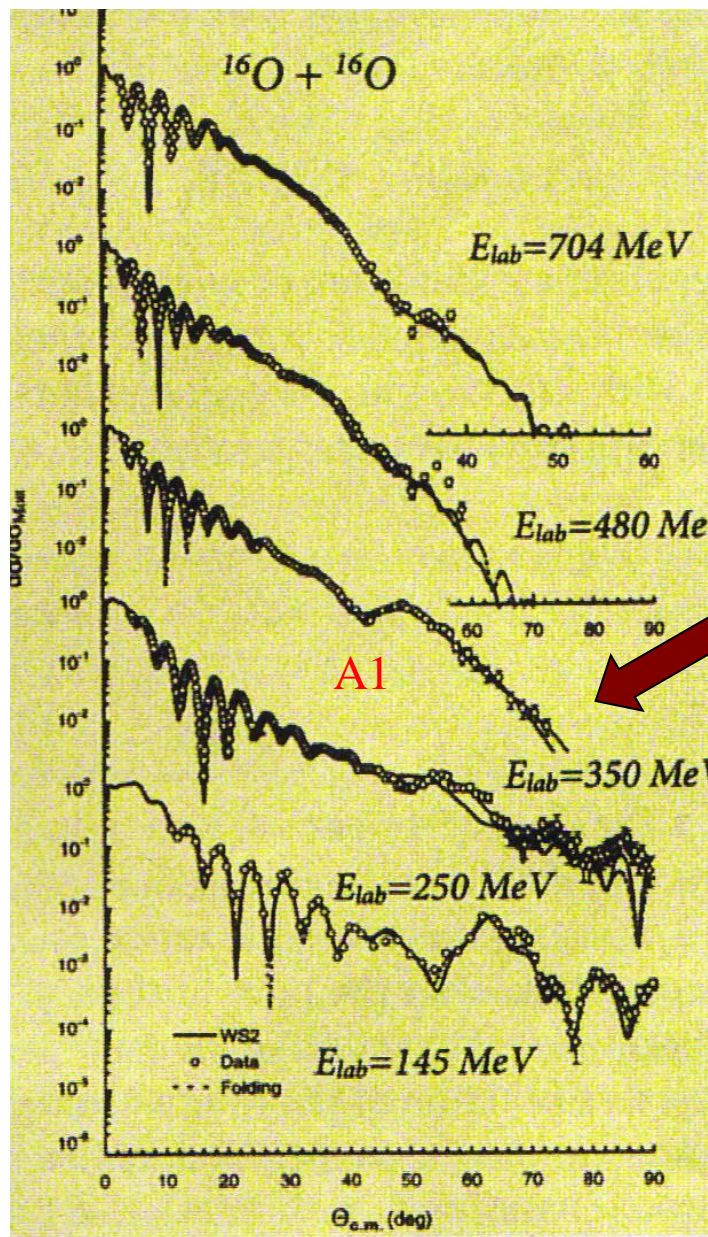
核反応研究会

重い粒子による虹散乱

$^{16}\text{O} + ^{16}\text{O}$ 散乱による核虹の発見

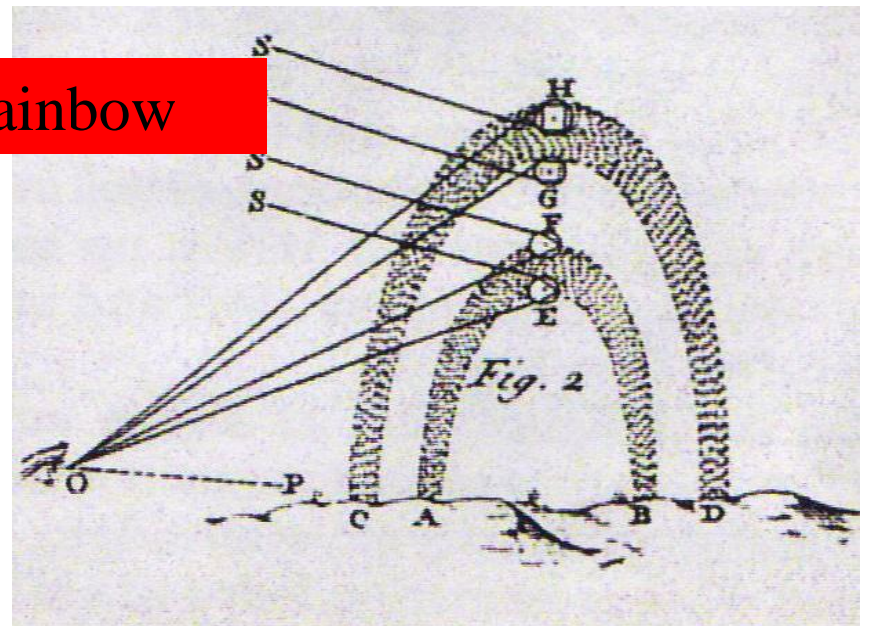
Berlin Hahn-Meitner 研究所

350MeV

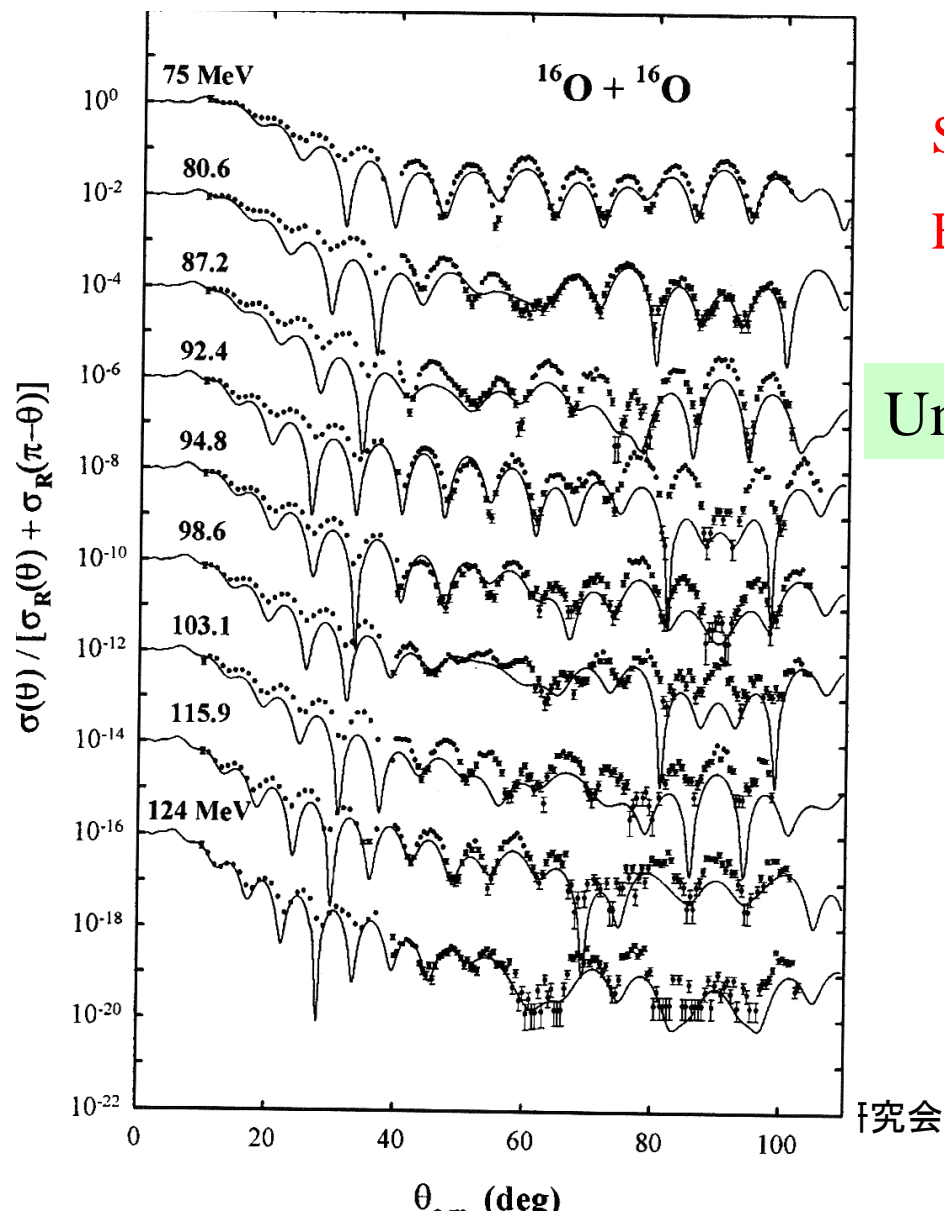


$E_L=145-704 \text{ MeV}$

rainbow



$^{16}\text{O}+^{16}\text{O}$ rainbow angular distributions

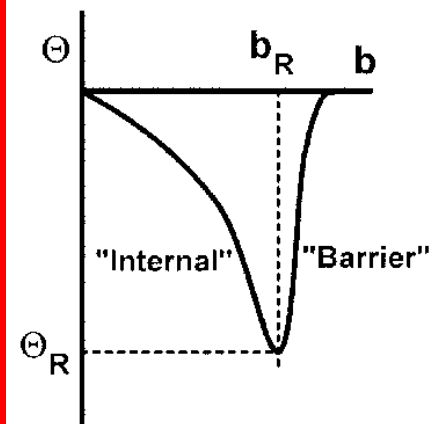
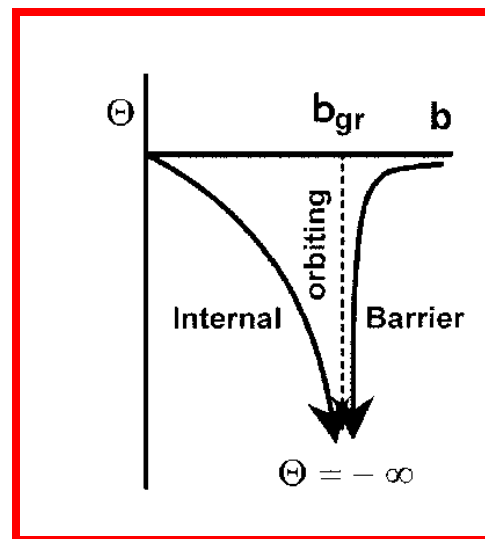
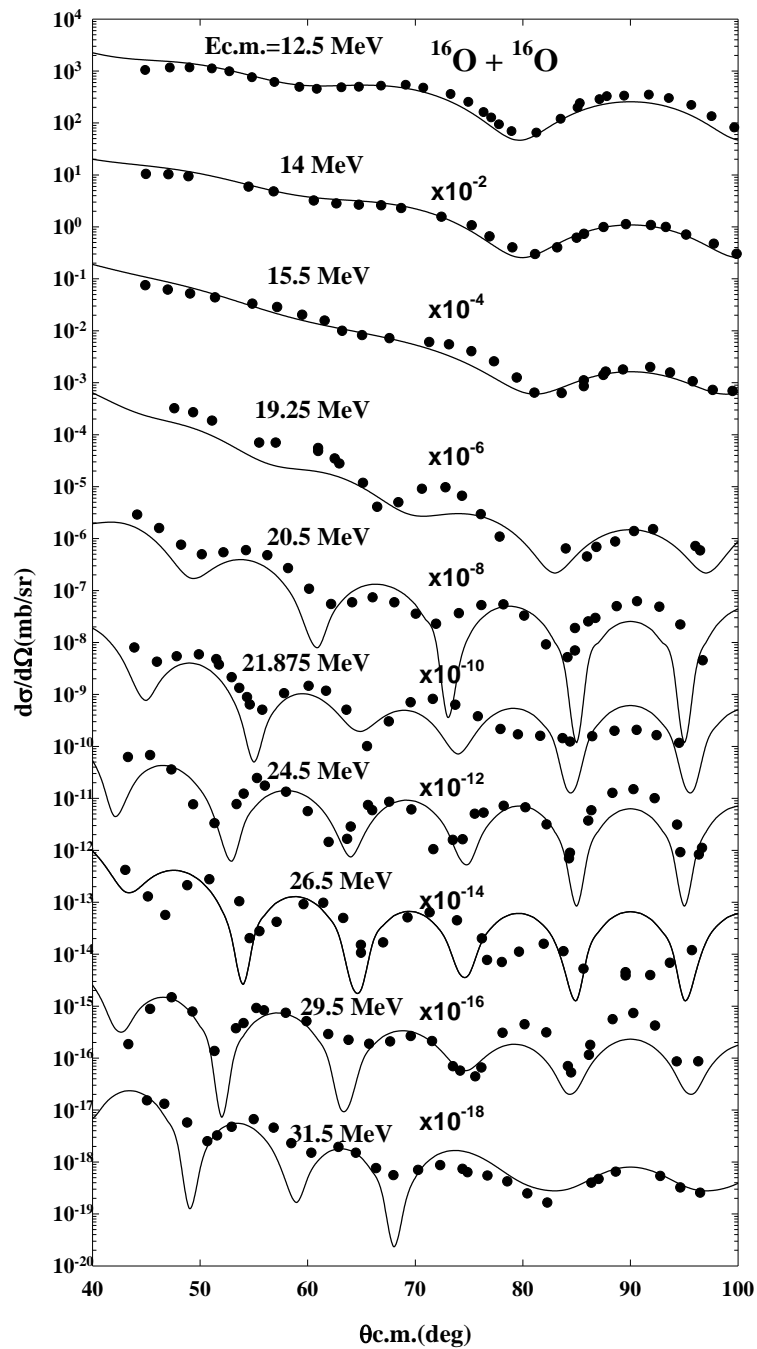


Strasbourg experiment

$E_L=75-124$ MeV

Unique global optical potential

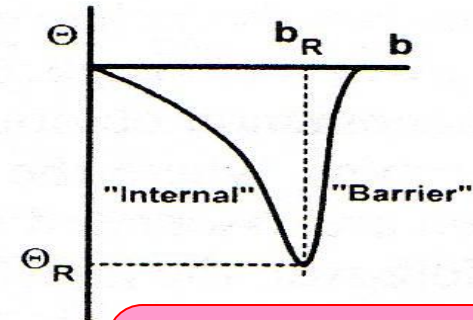
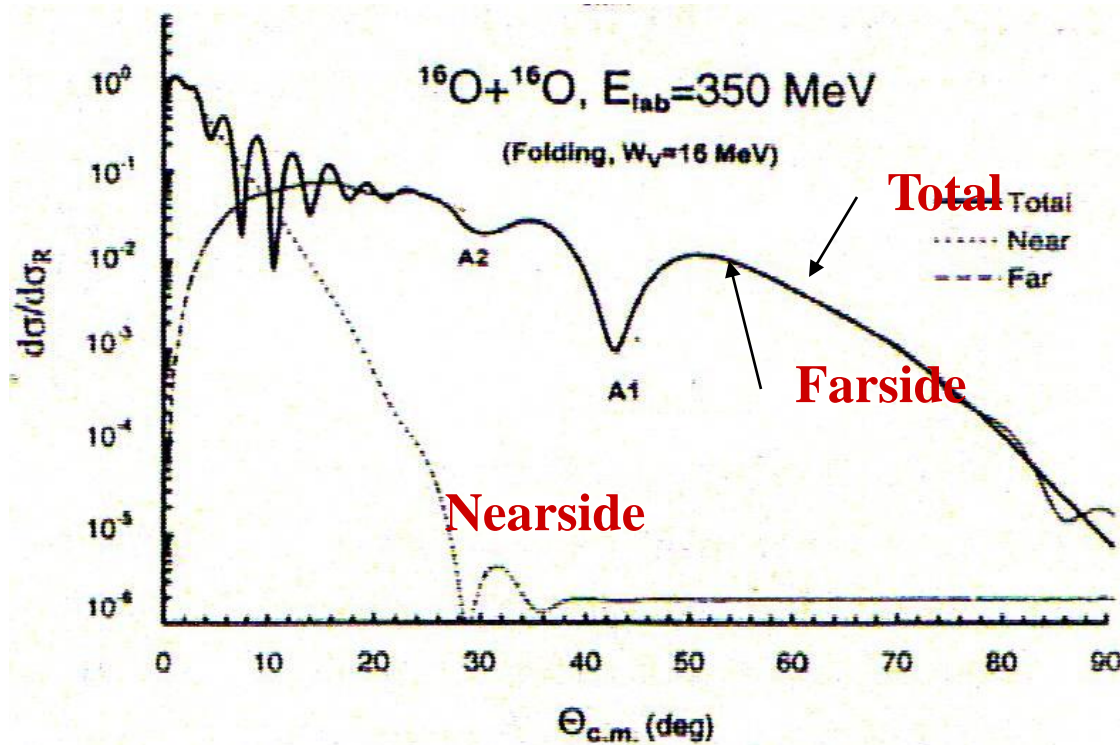
symmetrization



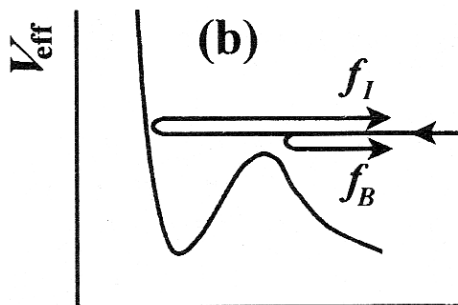
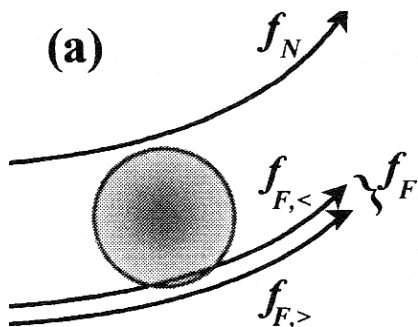
研究会

Fig.1

Mechanism of the nuclear prerainbows and rainbows



通常の虹と似ている
但し zeroth
order rainbow



Prerainbow
mechanism

Farside (internal)

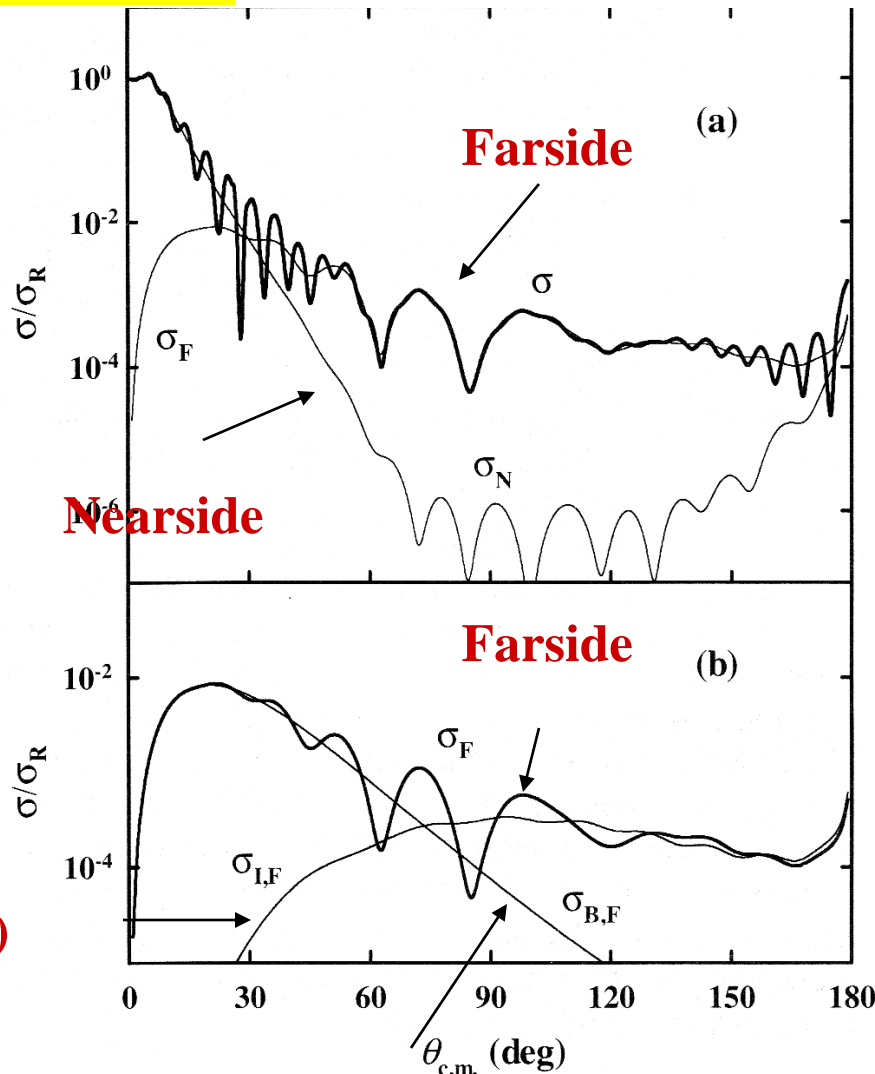
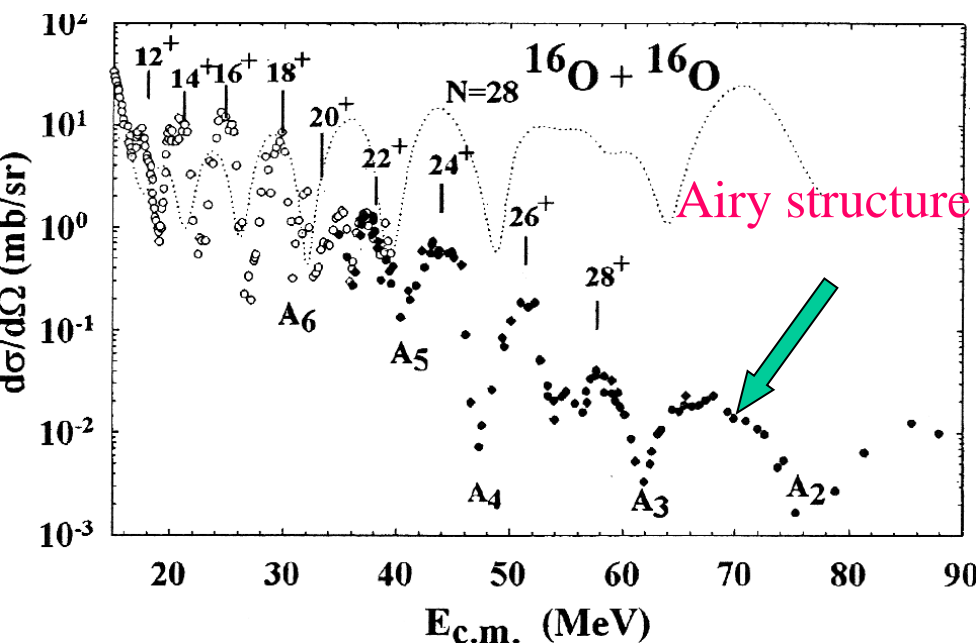


FIG. 3. (a) Ratio to Rutherford cross section of nearside (σ_N) and farside (σ_F) contributions to the unsymmetrized $^{16}\text{O} + ^{16}\text{O}$ elastic scattering cross section σ at 124 MeV; (b) farside contributions to the barrier ($\sigma_{B,F}$) and to the internal ($\sigma_{I,F}$) components of the full farside cross section σ_F .

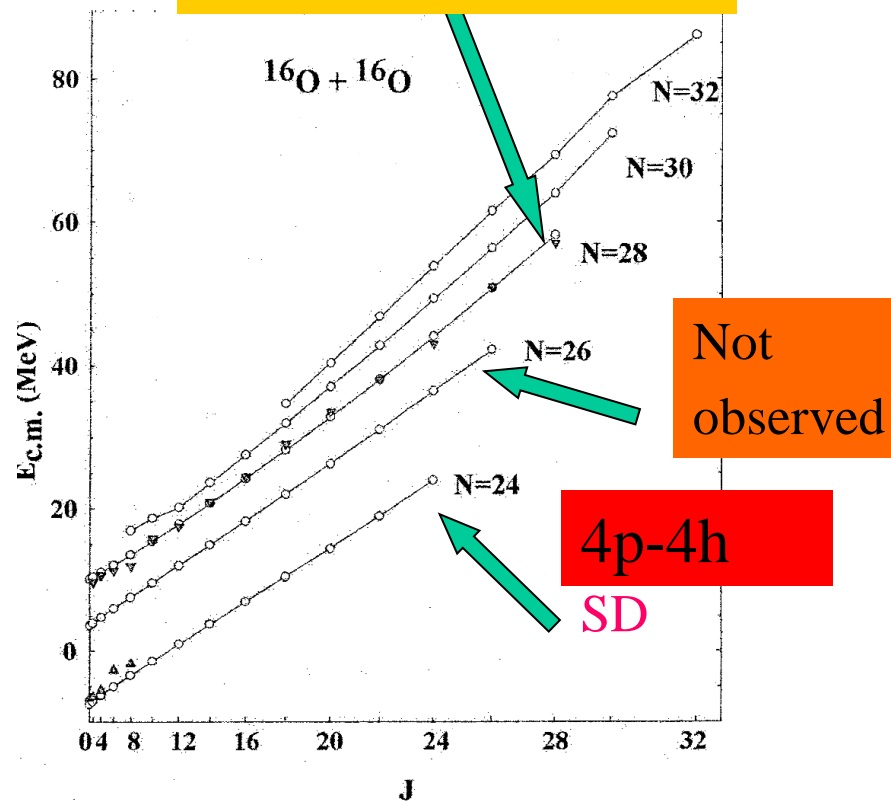
低いエネルギーではクラスター構造へ

Superdeformation with the $^{16}\text{O}+^{16}\text{O}$ cluster structure

Molecular resonances



Molecular resonances



光学

(光の)虹

1704



1900

1905

1924

1974

粒子

デカルト

ニュートン

ゼロ次の虹

エアリー

波

プランク

量子

ドブロイ

波

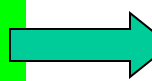
ゴールドバーグ

原子核の虹

新たな展開

ニュートンのゼロ次の虹

$\alpha + {}^{40}\text{Ca}$



${}^{16}\text{O} + {}^{16}\text{O}$



1. クラスタ構造とALAS・虹の統一 ($E = -\infty \rightarrow +\infty$ 、正負エネルギーの統一)

2. 軽い核と重い核のクラスタ構造の統一 (質量数 $A = 4 - 212$)



3. 地上の虹と核虹の統一 (マクロとミクロの虹の統一)

非弾性散乱における核虹の存在

Energy evolution Airy $\alpha + {}^{40}\text{Ca}$

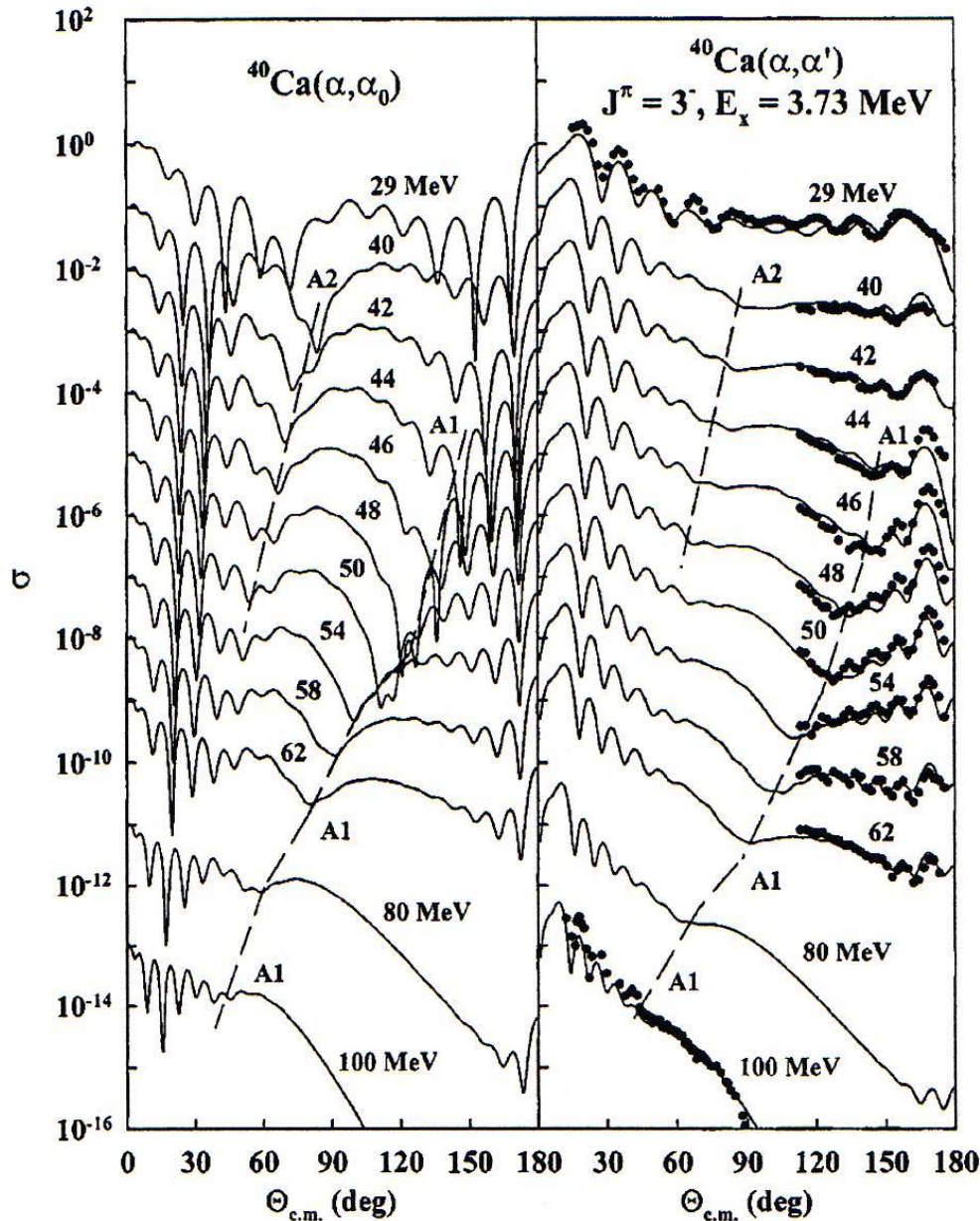


FIG. 4. Elastic (left) and inelastic ($J^\pi = 3^-, E_x = 3.73 \text{ MeV}$, right) $\alpha + {}^{40}\text{Ca}$ angular distributions between 28 and 100 MeV, showing the evolution with energy of the position of the A1 and A2 Airy minima; each successive angular distribution is shifted downwards by one or two decades (data at 29 MeV, from 40 to 62 MeV, and at 100 MeV from Refs. [22], [20,23], and [24], respectively).

B/I decomposition and inelastic Airy

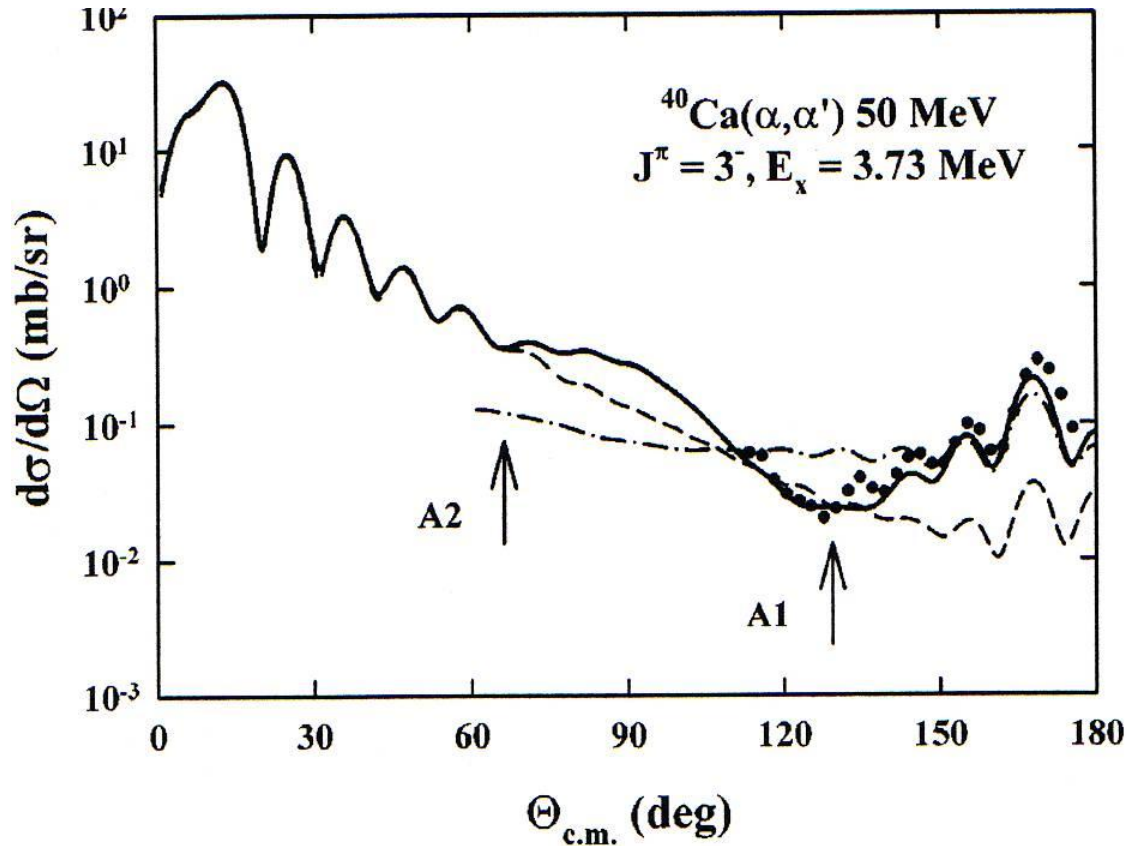


FIG. 5. Barrier-wave–internal-wave contributions to the $\alpha + ^{40}\text{Ca}$ inelastic angular distribution for excitation of the $J^\pi = 3^-, E_x = 3.73 \text{ MeV}$ state at 40 MeV incident energy (thick line: full cross section, dashed line: barrier-wave contribution, dash-dotted line: internal-wave contribution); the arrows point to the two inelastic Airy minima, which are seen to result from an interference between the barrier-wave and internal-wave contributions to the inelastic scattering amplitude.

弱束縛核における核虹の存在

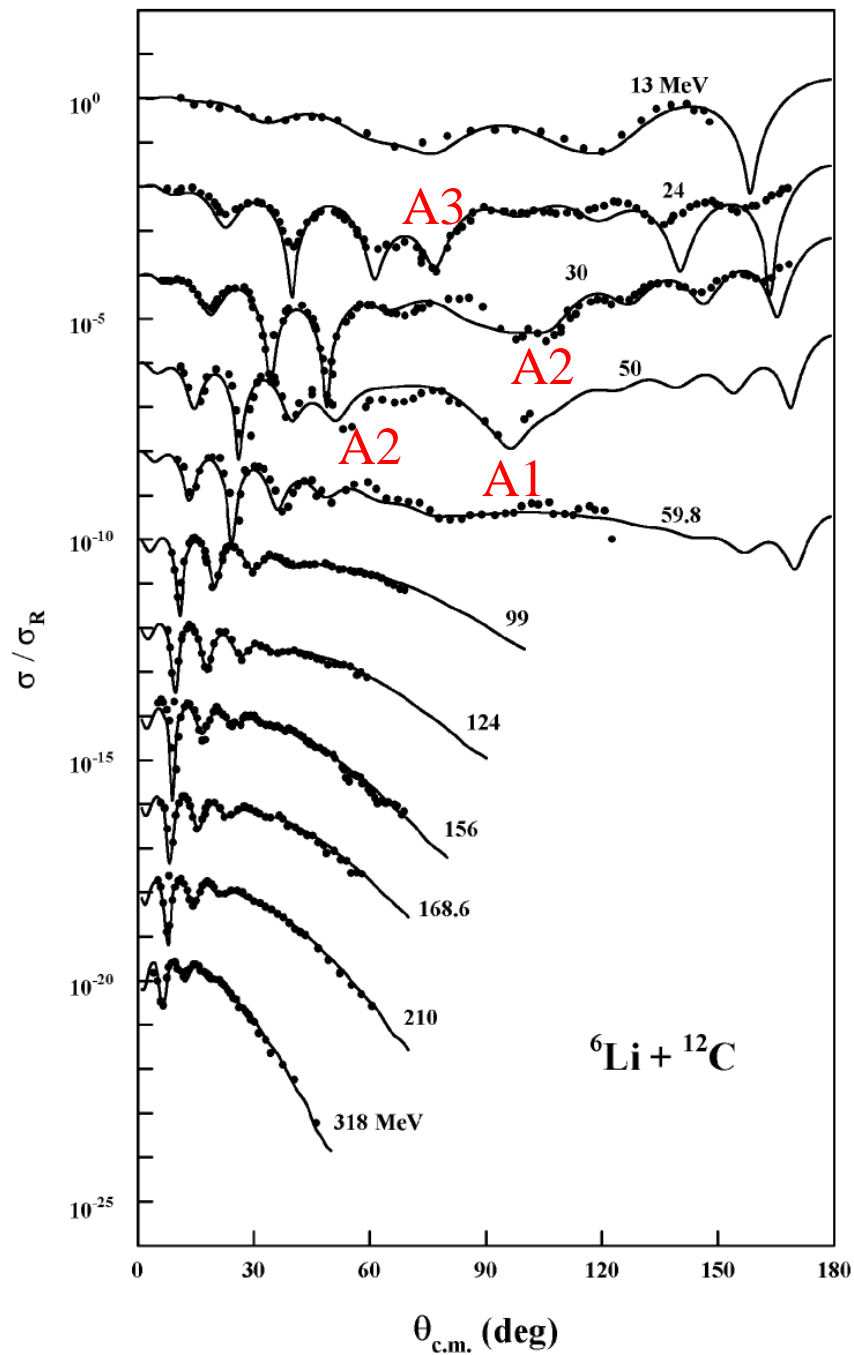
3個の典型で示すことにより概念の普遍性へ

- 1) α (軽い強束縛核)
- 2) ^{16}O (重い強束縛核)
- 3) ^6Li ^6He (弱束縛核)

^6Li

- 1) $\alpha + d$ が弱く束縛
- 2) 散乱で breakup が強い

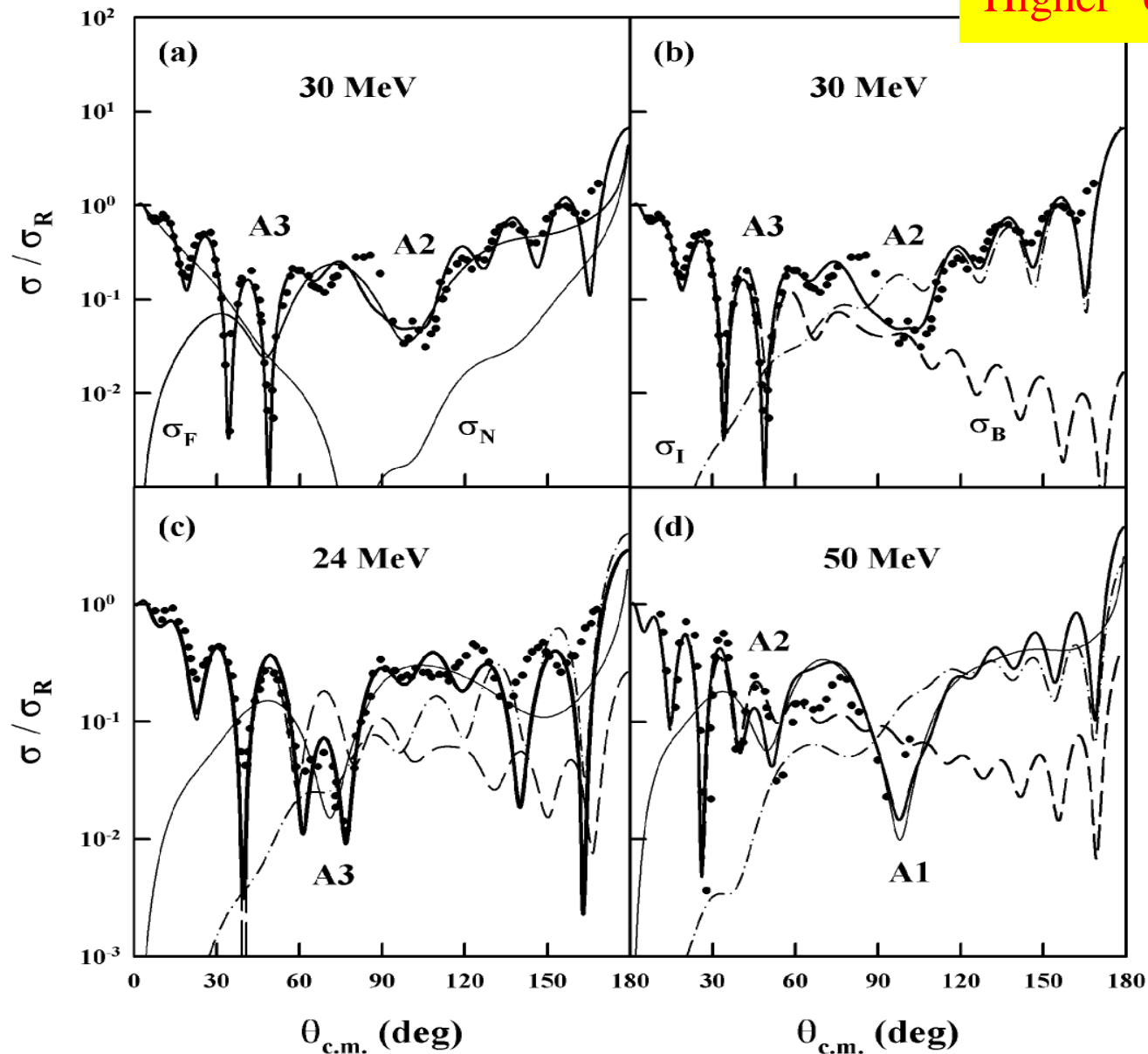
${}^6\text{Li}+{}^{12}\text{C}$ angular distributions



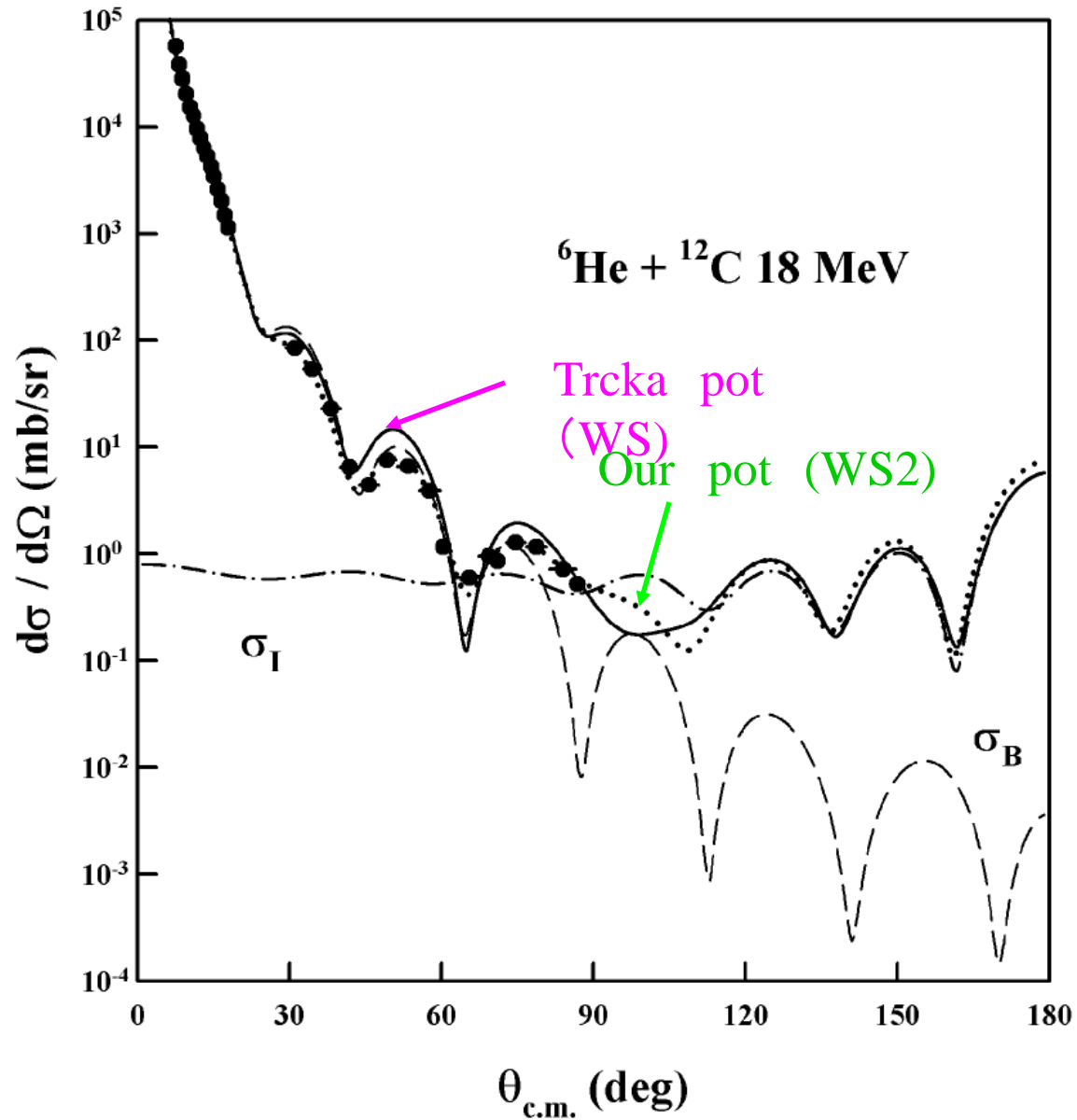
${}^6\text{Li} + {}^{12}\text{C}$ N/F B/F decomposition

${}^6\text{Li} + {}^{12}\text{C}$

Higher order Airy structure



${}^6\text{He} + {}^{12}\text{C}$ 18MeV



虹散乱は励起状態の構造検証に有用

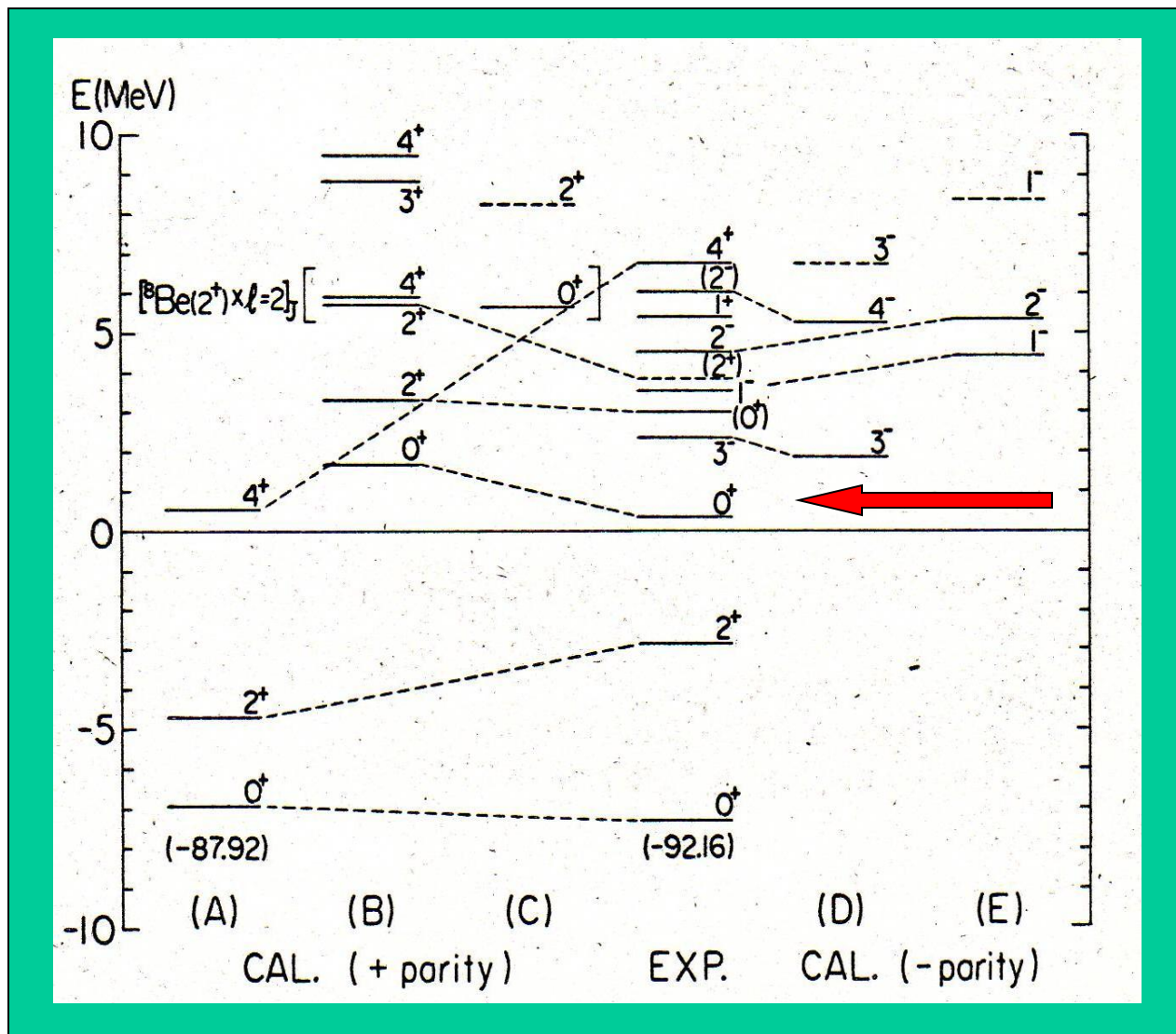
^{12}C の 3α 粒子のBose-Einstein 凝縮

1977

Uegaki 3 alpha cluster model

Energy level ^{12}C

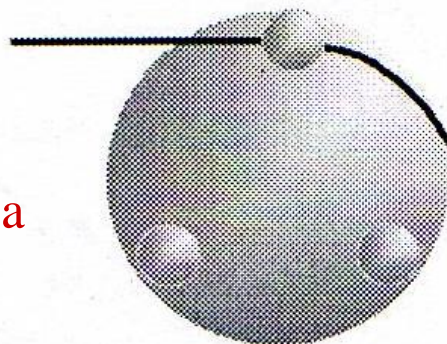
(PTP 57,1262(1977)) GCM



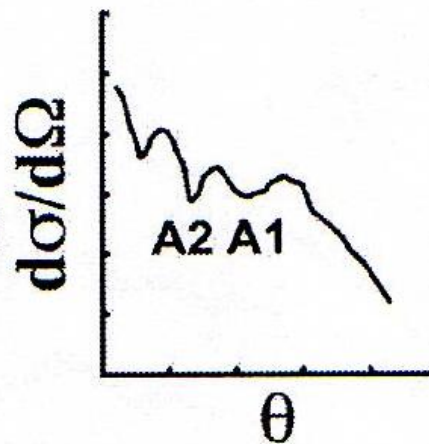
3α Hoyle state

Illustrative Figure of Airy structure and scattering

Rainbow from a dilute gas



Dilute density
(large lens)

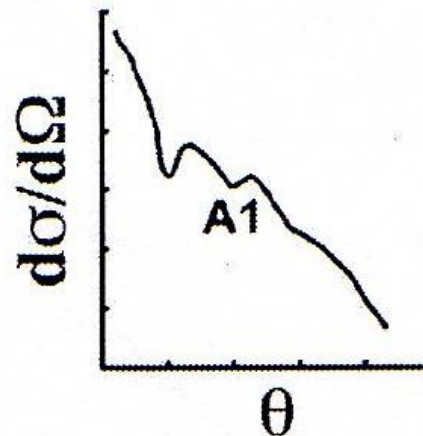


Airy minimum

Rainbow from a liquid



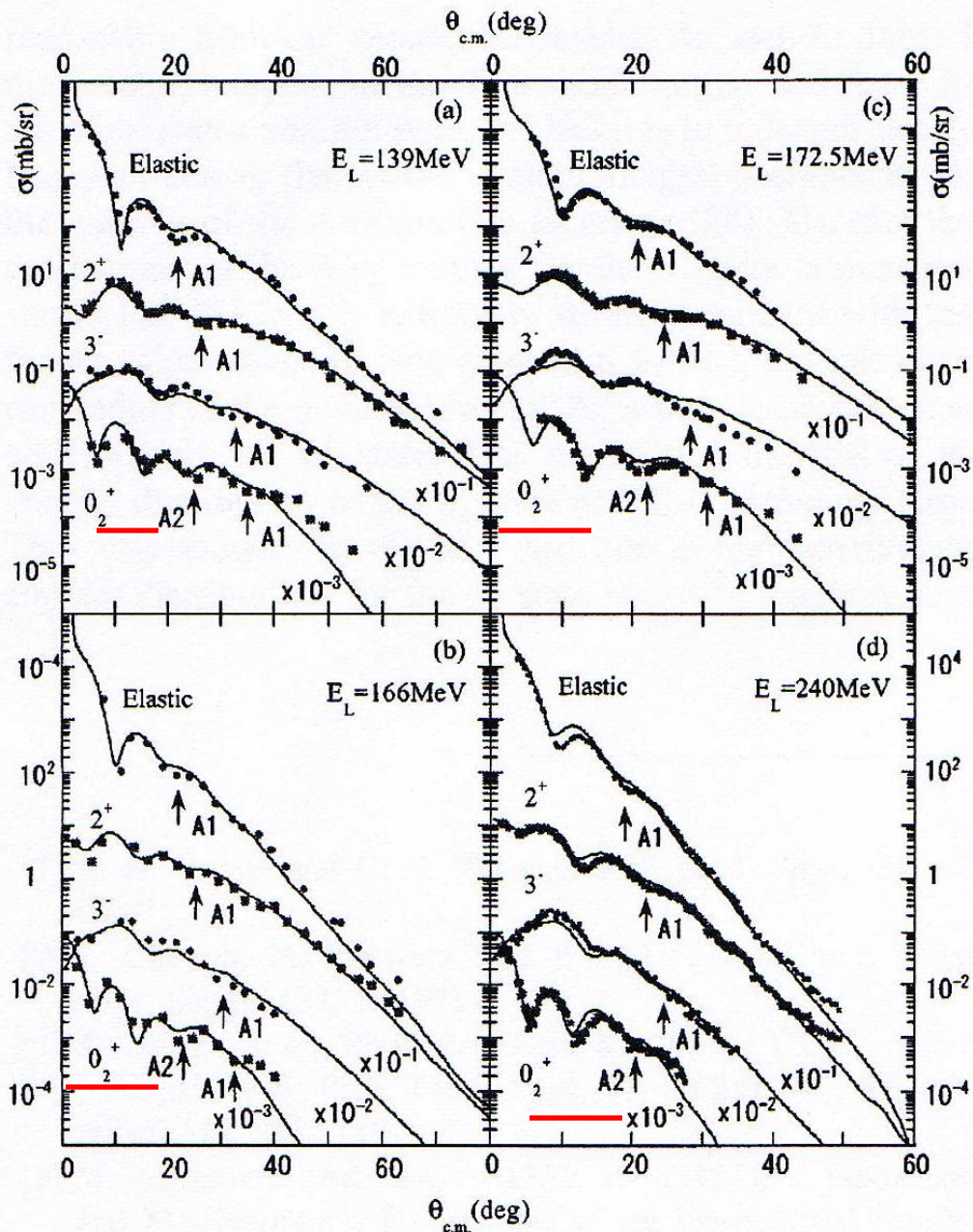
Normal density
(small lens)



Alpha + ^{12}C scattering

rainbow

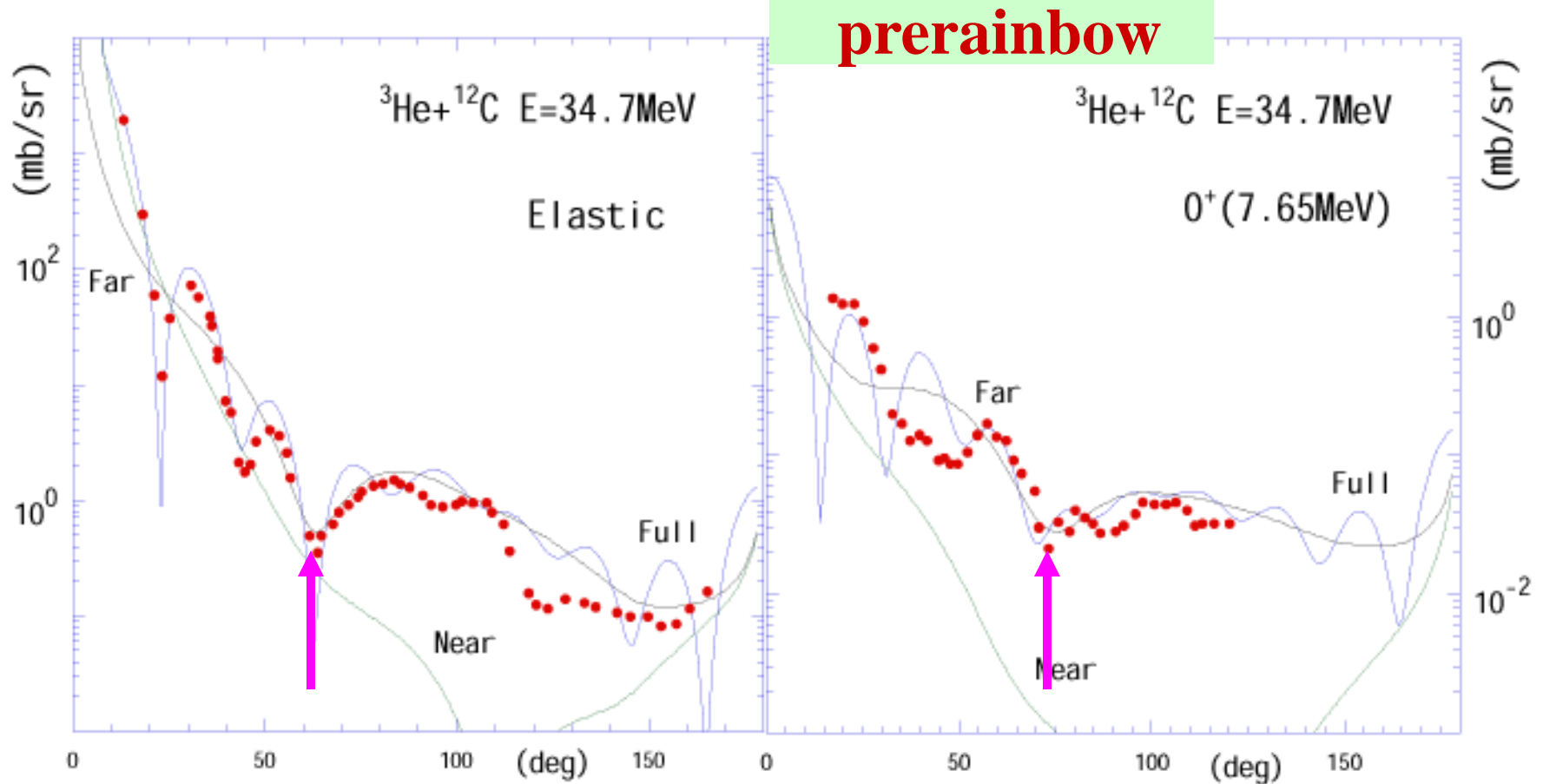
Airy minimum



2007

${}^3\text{He}+{}^{12}\text{C}$ scattering $E=34.7$ MeV

N/F decomposition



^{16}O の 4α 構造

有限系の原子核の α 粒子ではどうか？

1. 0^+ のみでなく **励起状態もともに**理解されるべき。
(部分のみでなく全体を見るべき: 部分と全体の弁証法)
2. 束縛状態近似ではなく**共鳴状態として正確に解くべき。**

1967

^{16}O の 4α 構造の研究状況:

Chevallier et. al. 4α linear chain model

VOLUME 160, NUMBER 4

Breakup of O^{16} into $\text{Be}^8 + \text{Be}^8$

P. CHEVALLIER AND F. SCHEIBLING

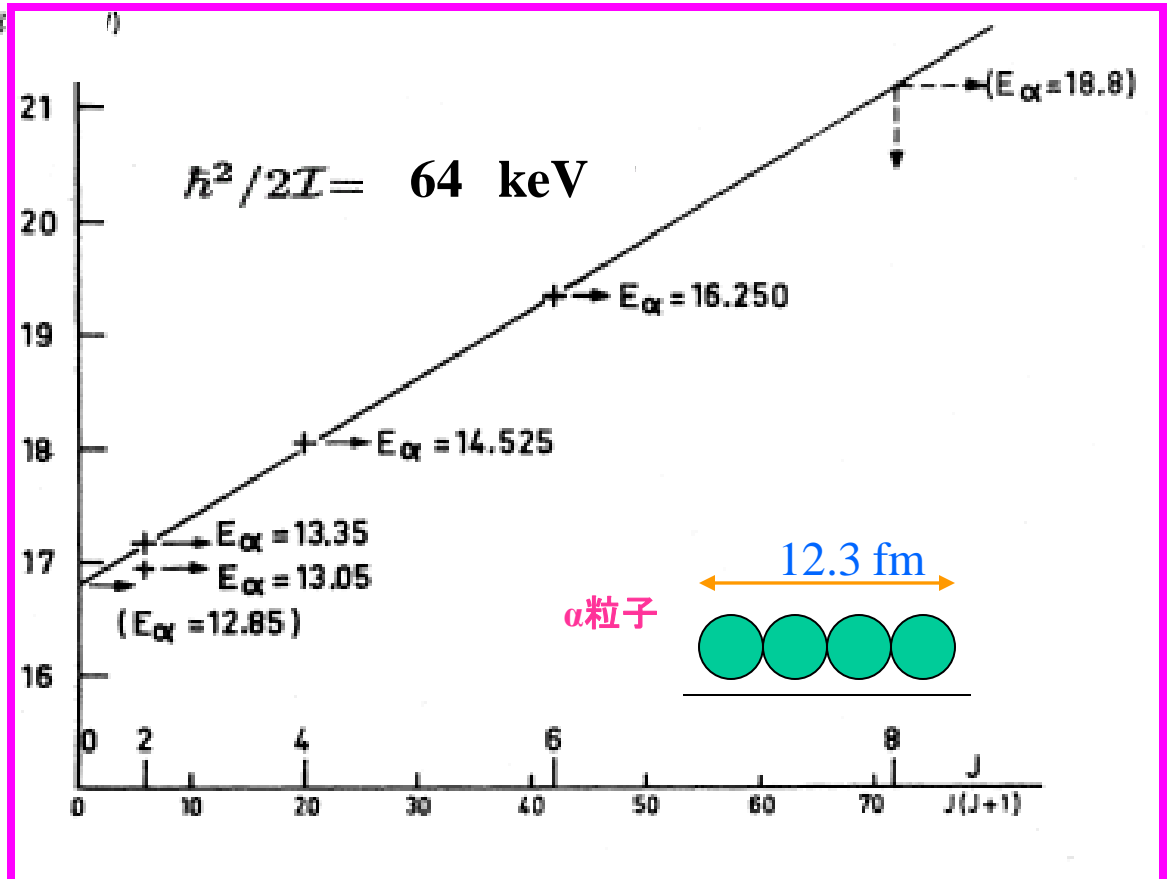
Institut de Recherches Nucléaires, Strasbourg-Cronembourg, France

AND

G. GOLDRING, I. PLESSER, AND M. W. SACHS*

The Weizmann Institute of Science, Rehovoth, Israel

(Received 27 January 1967)



1995

 ^8Be and α decay of ^{16}O

M. Freer, N.M. Clarke, N. Curtis, B.R. Fulton, S.J. Hall, M.J. Leddy, J.S. Pople, G. Tungate, and R.P. Ward
School of Physics and Space Research, University of Birmingham, Birmingham, B15 2TT, United Kingdom

P.M. Simmons and W.D.M. Rae
Department of Physics, Nuclear Physics Laboratory, University of Oxford, Keble Road, Oxford, OX1 3RH, United Kingdom

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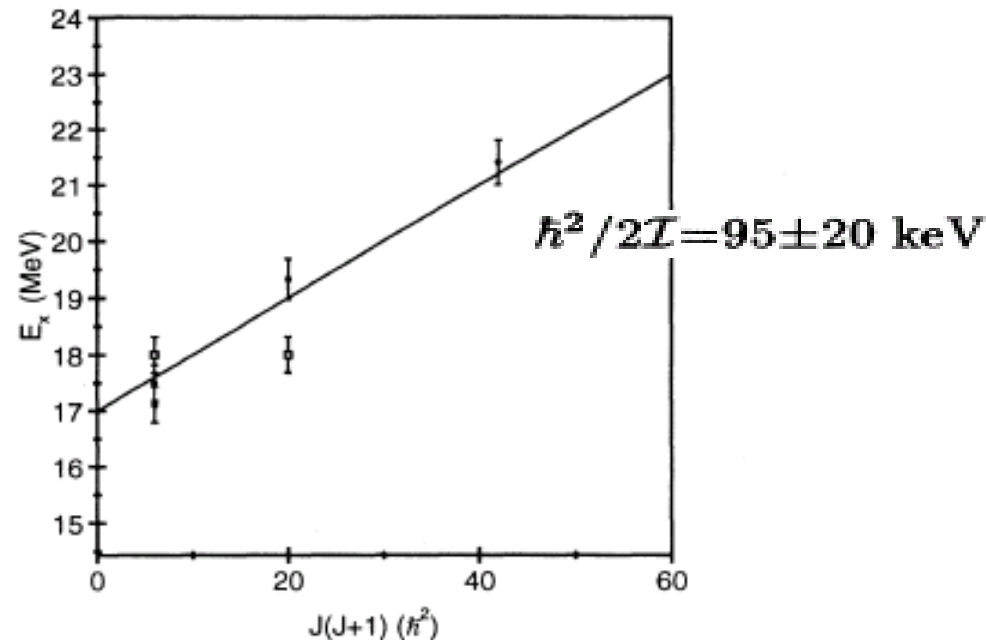


FIG. 8. Energy-spin systematics of the states for which spins were inferred. The open squares show the 18.0 MeV state with both $J=2$ and $J=4$.

^{16}O の $\alpha + ^{12}\text{C}$ (Hoyle) クラスタ構造

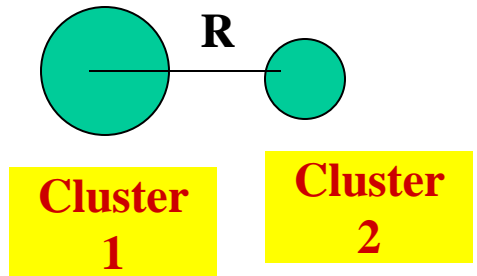
チャンネル結合法による $\alpha + ^{12}\text{C}$ 散乱の解析

- ^{12}C の波動関数 3α RGM~ボーズ凝縮の波動関数
 - 密度依存DDM3Y有効相互作用による畳込み

Coupled channel equations

$$\Psi = \sum_i \varphi(\alpha) \varphi_i(^{12}\text{C}) \chi_i(\mathbf{R}), \quad (1)$$

$$\left[-\frac{\hbar^2}{2\mu} \nabla^2 + U_{ii}(\mathbf{R}) - (E - \epsilon_i) \right] \chi_i(\mathbf{R}) = -\sum_{j \neq i} U_{ij}(\mathbf{R}) \chi_j(\mathbf{R}). \quad (2)$$



Double folding potential

$$V_{ij}(\mathbf{R}) = \int \rho_\alpha(\mathbf{r}_\alpha) \rho_{i,j}(\mathbf{r}_T) v(\mathbf{R} - \mathbf{r}_T + \mathbf{r}_\alpha) d\mathbf{r}_T d\mathbf{r}_\alpha, \quad (3)$$

renormalization factor $N_R + iN_I$

$$U_{ij}(\mathbf{R}) = N_R V_{ij}(\mathbf{R}) + iW(\mathbf{R}) \delta_{ij}, \quad (4)$$

DDM3Y effective interaction

$$v_{NN}(E, \rho; s) = g(E, s) f(E, \rho). \quad f(E, \rho) = C(E) [1 + \alpha(E) e^{-\beta(E)\rho}],$$

取り入れる ^{12}C のchannel

g.s., 2_1^+ (4.44 MeV), 3^- (9.65 MeV), 0_2^+ (7.65 MeV) and 2_2^+ (10.3 MeV). The absorption due to the coupling to all the other

Imaginary potential

$$E_L = 18 \text{ MeV}$$

open channels, i.e., $p + ^{15}\text{N}$, $n + ^{15}\text{O}$ and $d + ^{14}\text{N}$ channels,

$$N_I = 0.045.$$

Real potential

$$E_\alpha = 139, 166 \text{ and } 172.5 \text{ MeV}$$

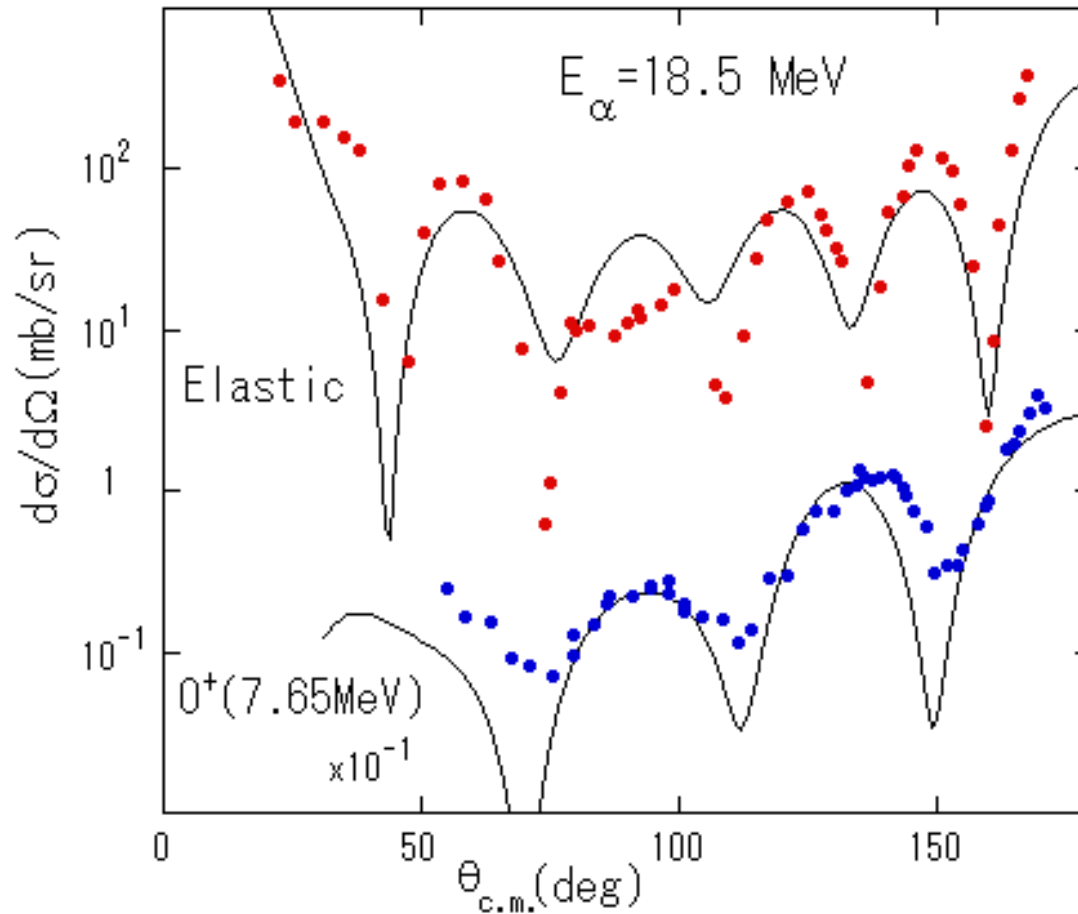
$$N_R = 1.23 - 1.26.$$

$$E_L = 18 \text{ MeV}$$

$$N_R = 1.398$$

$\alpha + {}^{12}\text{C}$ 散乱

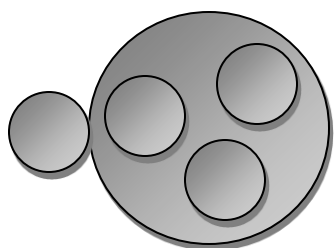
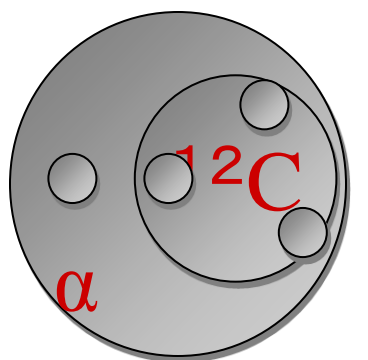
$E_L = 18.5 \text{ MeV}$ (lowest energy) の解析



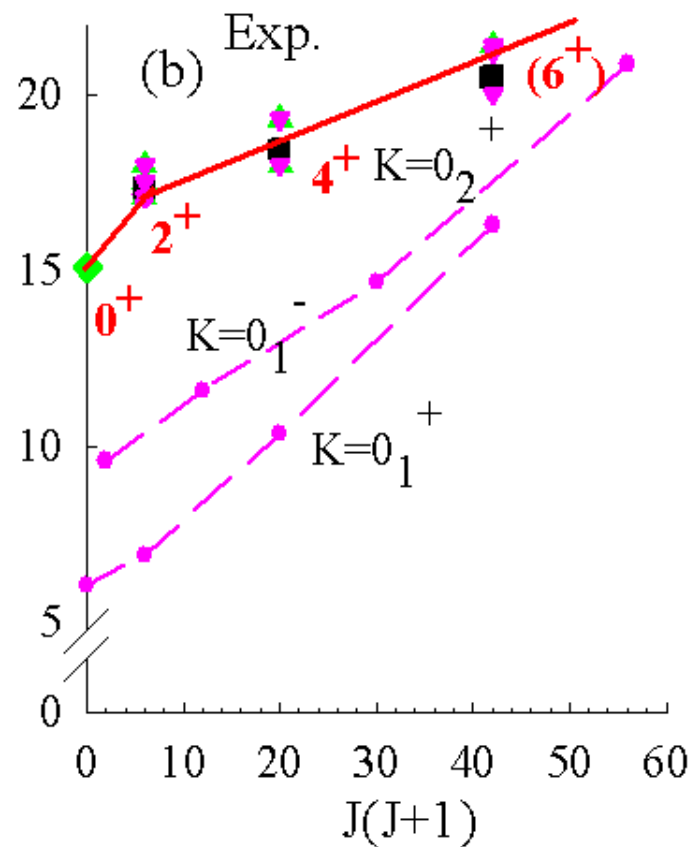
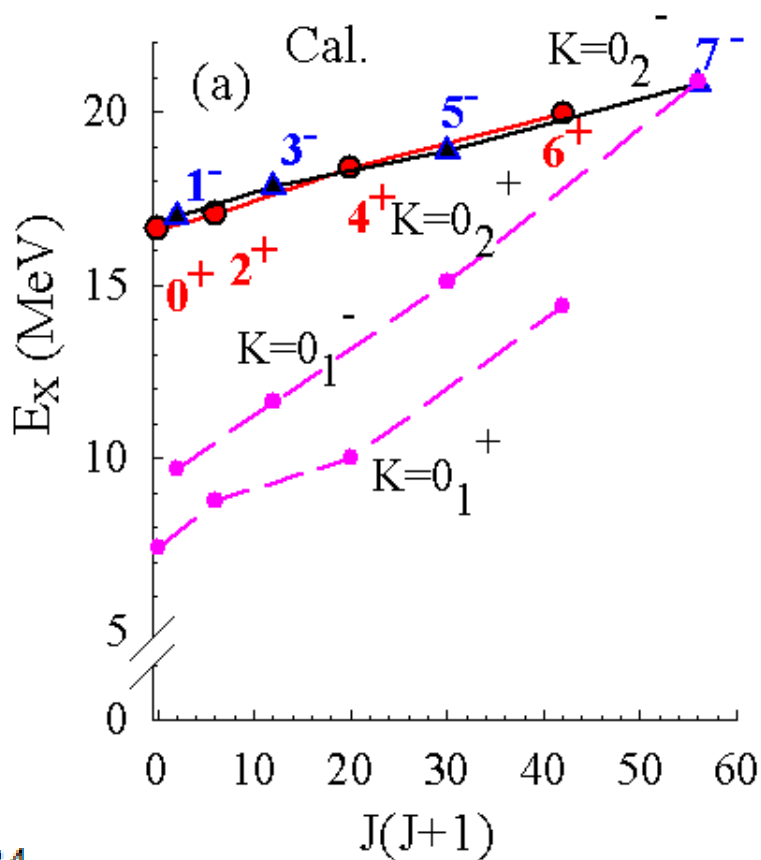
^{16}O の $\alpha + ^{12}\text{C}$ (Hoyle) クラスタ構造 をもつエネルギー準位

$\alpha + ^{12}\text{C}$ (Hoyle)

^{16}O



$\alpha + ^{12}\text{C}$ (g.s.)



collaborator

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まとめ

- 1) 原子核の虹ではプレ虹が見られる、干渉構造 ALAS、クラスター構造
- 2) 非弾性の散乱でも核虹が見られるしくみは同じ
- 3) ${}^6\text{Li}$ など弱束縛核でも見られる
- 4) 核虹の研究は核間相互作用の決定のみならず核構造研究にも有用である
- 5) ${}^{16}\text{O}$ の 4α 閾値近傍に local condensate $\alpha + {}^{12}\text{C}$ (Hoyle)クラスター構造をもつ状態が存在する