量子クラスターで読み解く物質の階層構造スクール

2019.3.7

原子核階層はなぜできたのか？ ―バリオン間力（核力）の起源を探る

Why is the hierarchy of nuclei born? -- investigating the baryon-baryon interactions (nuclear force) --

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Tohoku Univ.,   H. Tamura

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物質階層はなぜできるのか？
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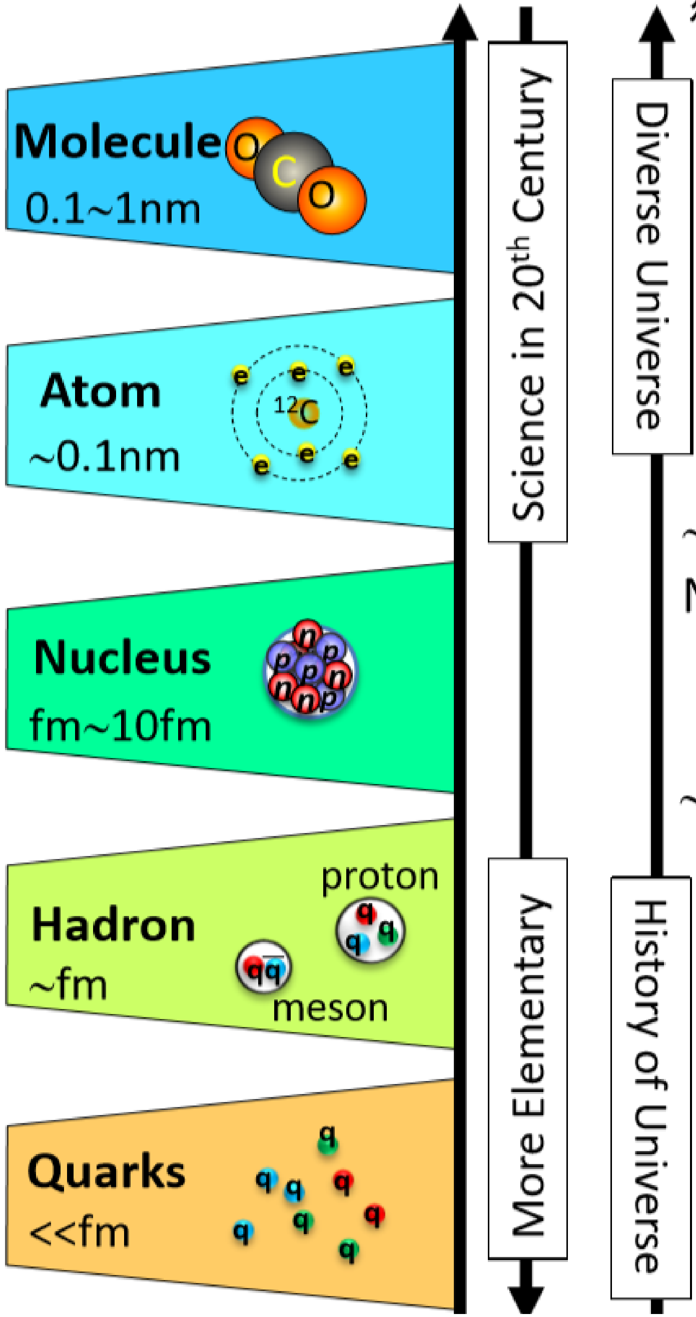
Studies of baryon-baryon interactions with strangeness

物質階層はなぜできるのか？
Why is the hierarchy of matter formed?

Why hierarchy is formed in quantum particles？



微視的粒子の世界に階層構造がどうして形成されたのか

Fundamental Question But Unresolved

→*Not necessarily investigated*

- *Research Areas : Independently evolved*
- *Connection between hierarchies: Unclear*

~380kY : Clear up of the Universe 宇宙の晴上がり
Nucleus+electrons →Atom→Molecule

~3min : Big Bang Nucleosynthesis ビックバン元素合成
nucleon (p, n) →^{4}He nucleus

~0.01ms : QCD Phase Transition QCD相転移

Big Bang

slide by 中村隆司

階層出現のメカニズム（核子→αクラスター）

Mechanism for emergence of hierarchy (nucleons->α cluster)

N-N force (核力)

大きなスピン・アイソスピン依存性

Large spin-isospin dependence

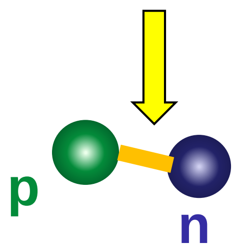
【テンソル力】tensor force

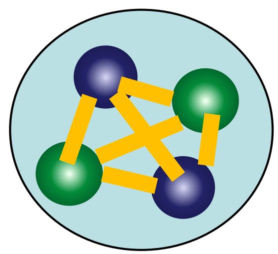
>>

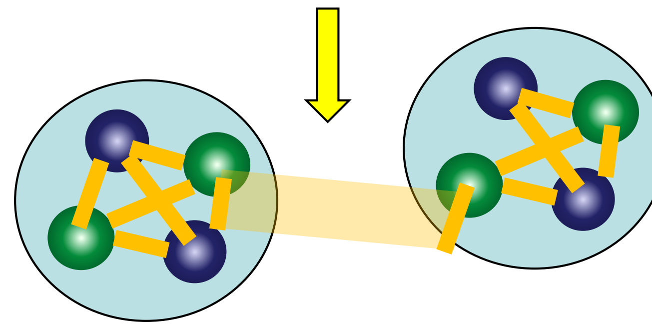
α−α force

核力のスカラー成分のみ

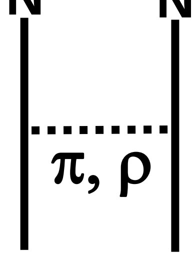
Scalar component of nuclear force only







α粒子内で

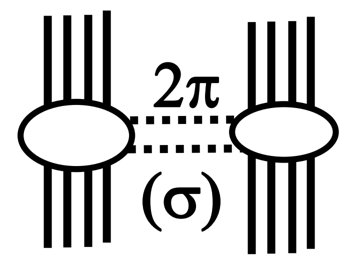


スピン・アイソスピンが中和

(S=0,T=0)

shell close[$(0s)^2(0s)^2$]も安定化

Neutralization (saturation) of spin-isospin in α



階層出現のメカニズム (クォーク→ハドロン)

Mechanism of emergence of hierarchy (quark->hadron)

クォーク間力 q-q force

グルーオン(色付き)交換

(カラー交換)

gluon (color) exchange

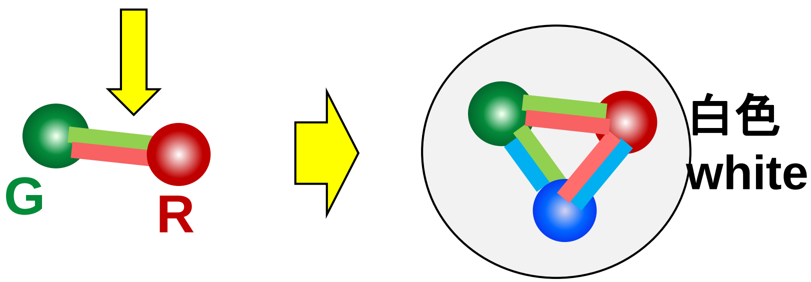
>>

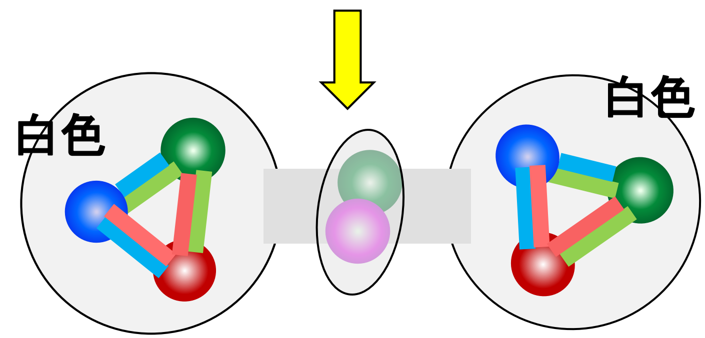
ハドロン間力 hadron-hadron force

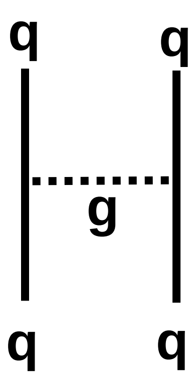
中間子(白色qq^{bar})交換

(クォーク交換)

meson exch.(colorless quark exch.)





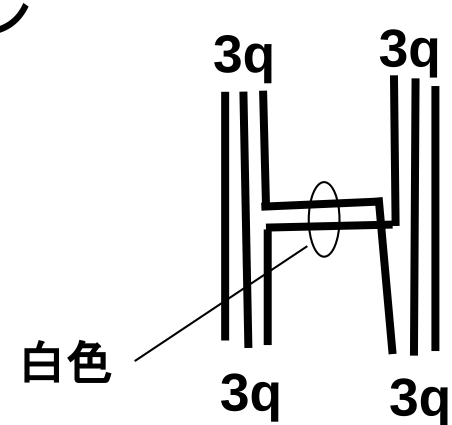


カラー中和 (白色)＝ハドロン

グルーオン交換力

(カラーに働く)は飽和。

Color neutral (white) = Hadron.
Gluon exch. force saturated.



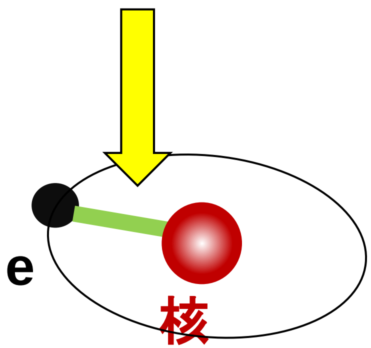
階層出現のメカニズム (1原子分子→凝縮系)

Mechanism of emergence of hierarchy
(single atomic molecule -> condensed matter)

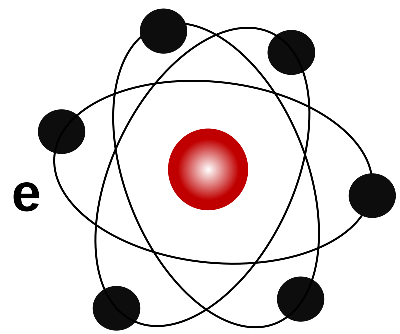
核・電子間クーロン力 **>>** **中性分子間の力**

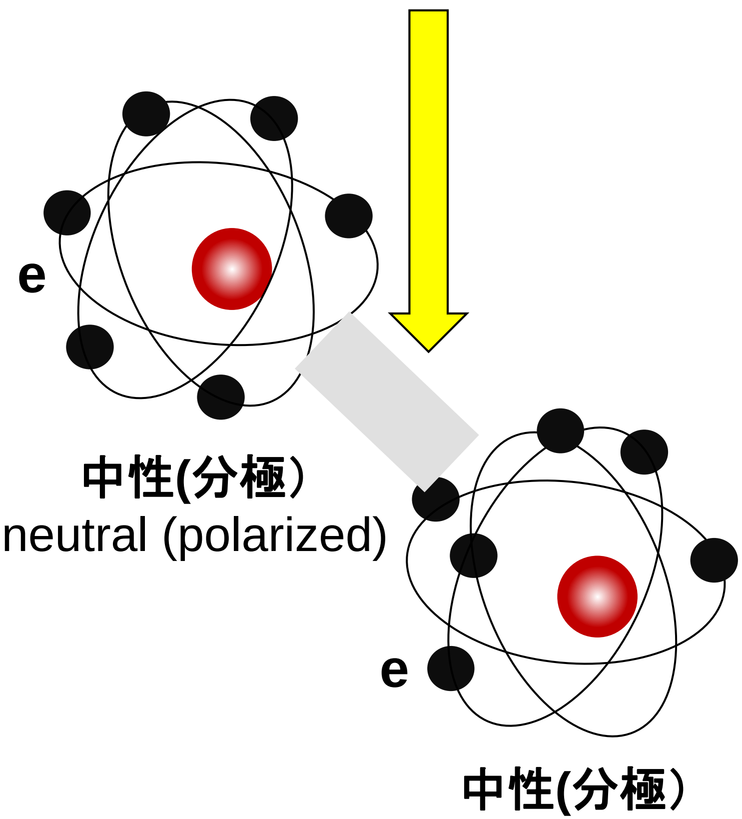
Nucleus-electron Coulomb

Van der Waals力



中性





原子(1原子分子)内でクーロン力が飽和。

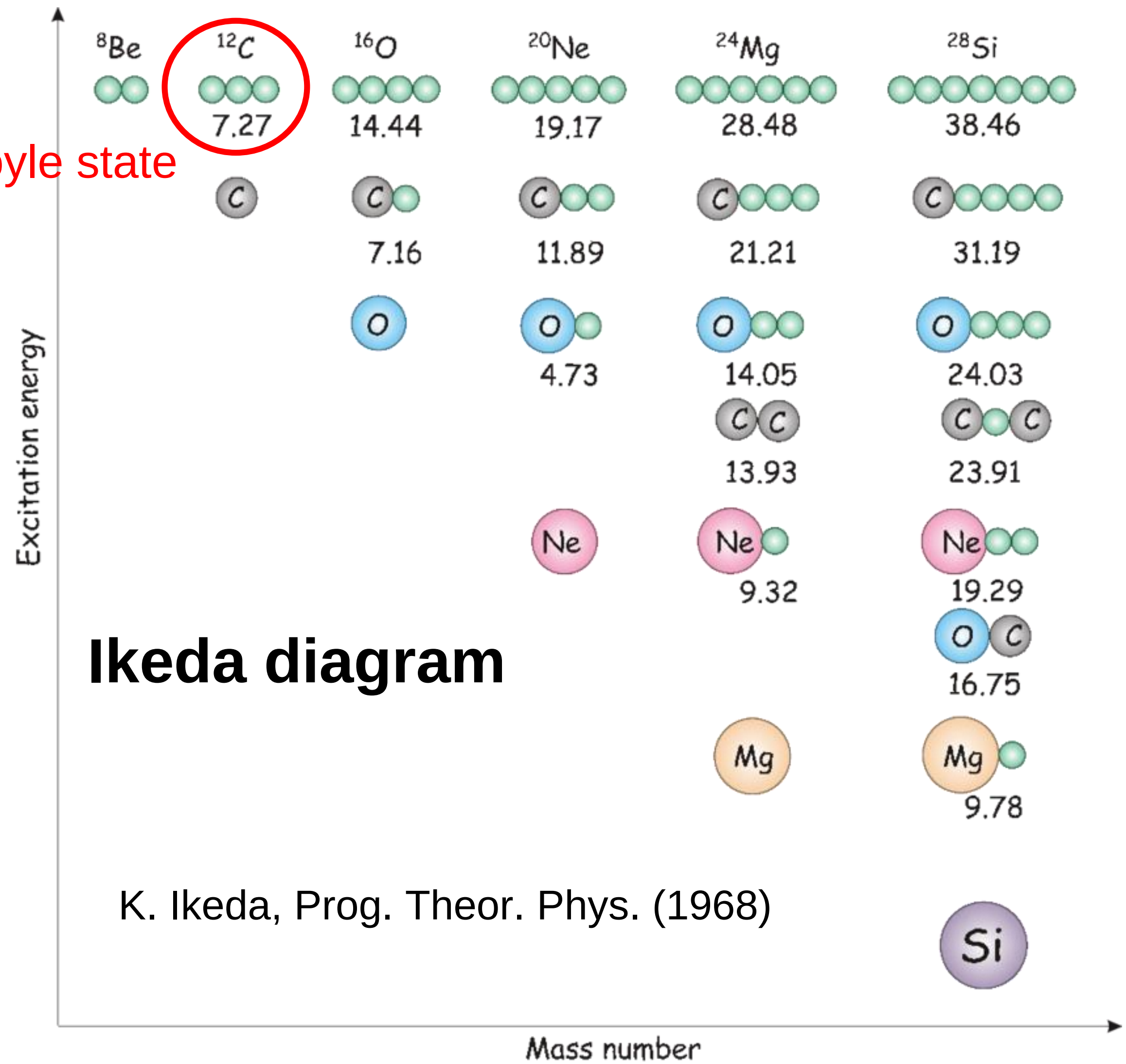
外から見ると、中性。

Coulomb force saturated.
Charge neutral.

Ikeda's threshold rule (池田閾値則)

アルファクラスターの集合体に分かれるエネルギー閾値のすぐ近くに、
そのクラスターに分かれた構造を持つ状態が存在する。

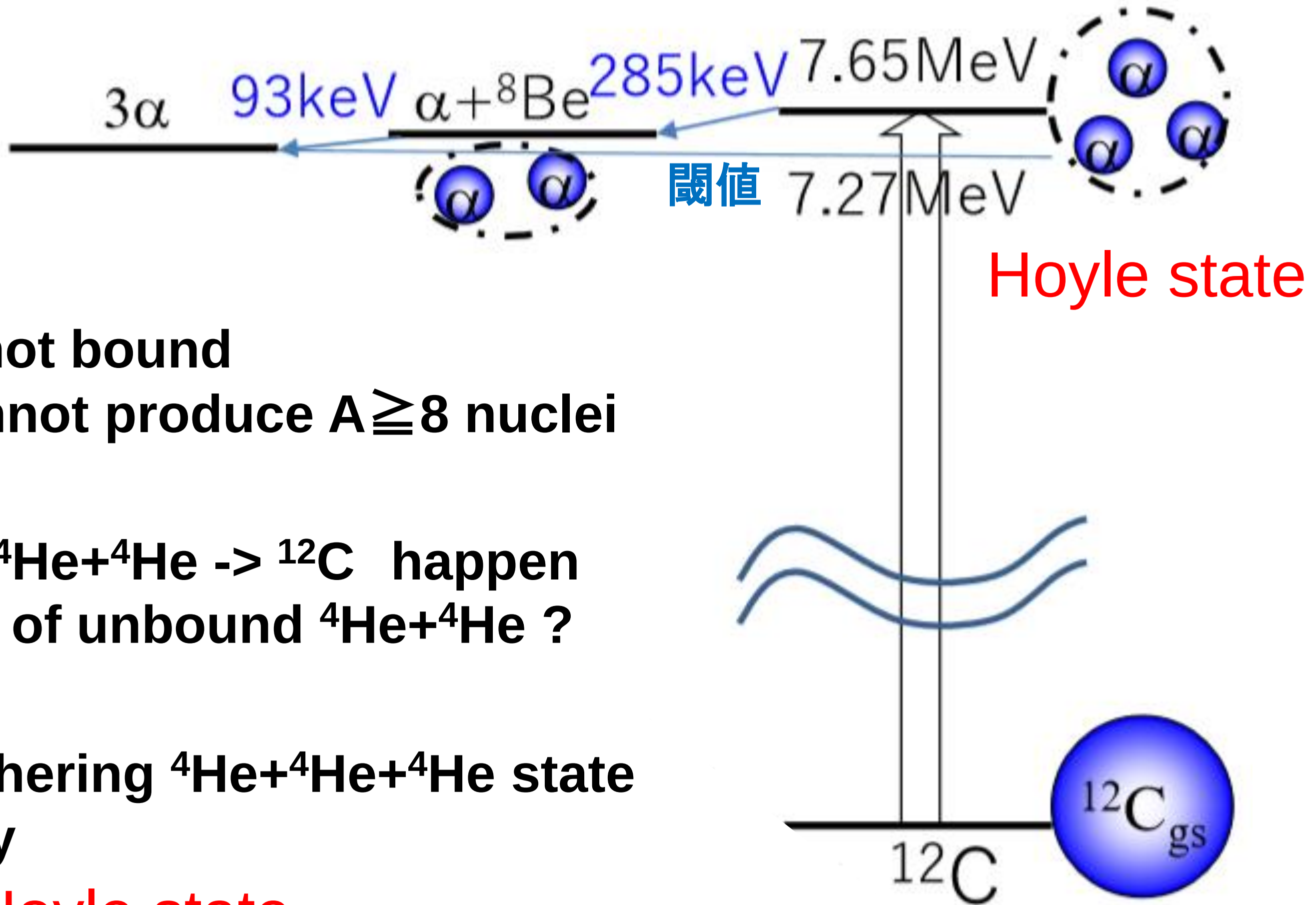
Close to the cluster decay threshold, a state with this clustering structure exists.



Ikeda diagram

K. Ikeda, Prog. Theor. Phys. (1968)

alpha cluster and Hoyle state



^{8}Be (^{4}He+^{4}He) is not bound
→ Big Bang cannot produce A≧8 nuclei

Why does ^{4}He+^{4}He+^{4}He -> ^{12}C happen in stars in spite of unbound ^{4}He+^{4}He ?

Loosely gathering ^{4}He+^{4}He+^{4}He state is necessary

Hoyle state

Subsystemに分解する閾値の周辺に現れるエキゾティックなハドロン励起状態

Exotic hadrons appearing close to the bound threshold of subsystems

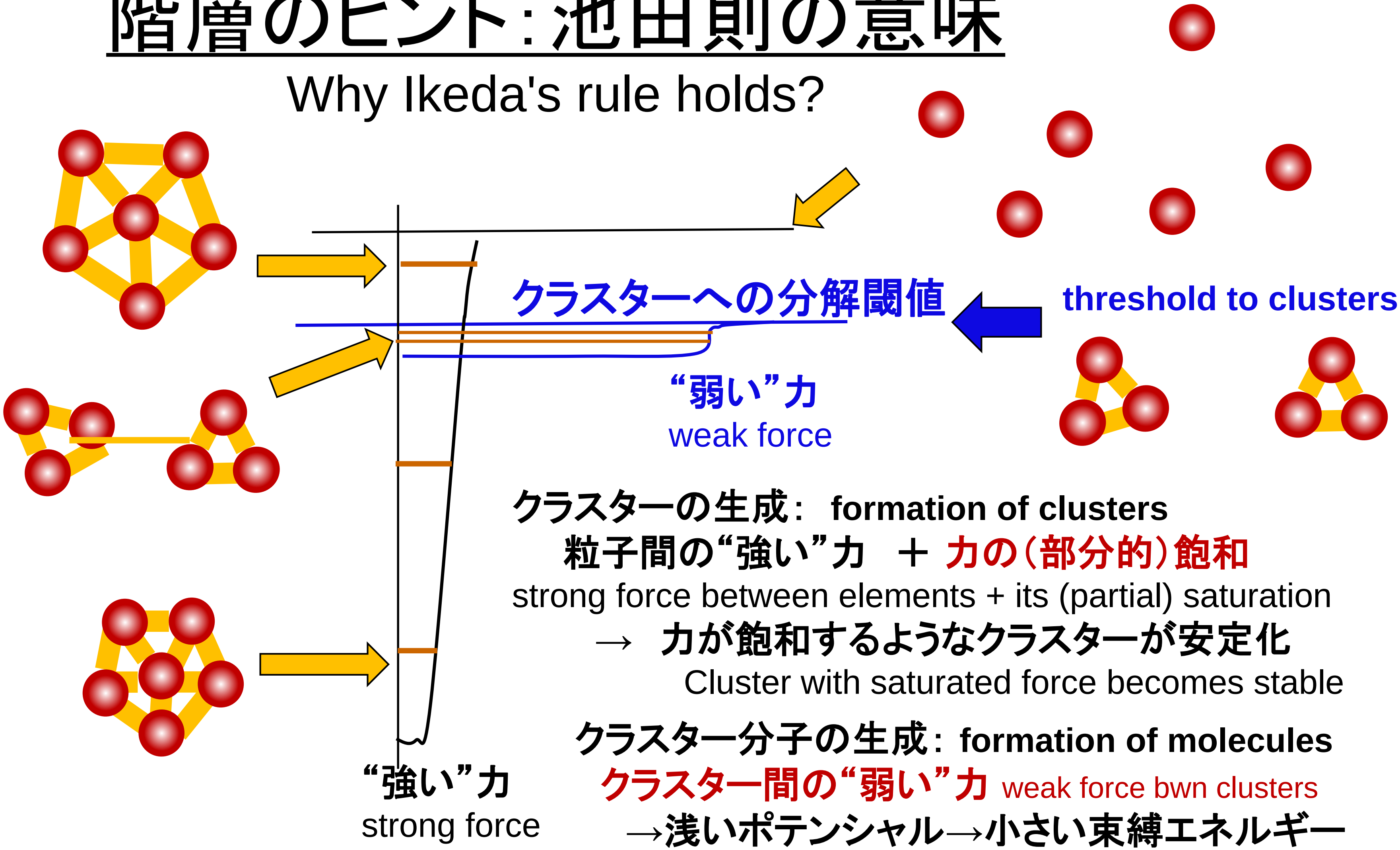
Λ*(1405)	K-(494) p(938) =1432 MeV
N*(1440)	σ(500) N(940) =1440
X(3872)	$\bar{D}_0$(1865) D_0*(2007) =3872
Z_c(3900)	$\bar{D}_0$(1865) D_0*(2007) =3872
Z_c(4020)	$\bar{D}_0$*(2007) D_0*(2007) =4014
Z_b(10610)	$\bar{B}_0$(5280） B_0*(5325) =10605
Z_b(10650)	$\bar{B}_0$*(5325) B_0*(5325) =10650

これら subsystemsの分子状態（束縛or共鳴状態）か？

molecular (bound/resonance) state of these subsystems?

階層のヒント：池田則の意味

Why Ikeda's rule holds?



クラスターの生成： formation of clusters

粒子間の“強い”力　＋ 力の（部分的）飽和

strong force between elements + its (partial) saturation

→　力が飽和するようなクラスターが安定化

Cluster with saturated force becomes stable

クラスター分子の生成： formation of molecules

クラスター間の“弱い”力 weak force bwn clusters

→浅いポテンシャル→小さい束縛エネルギー

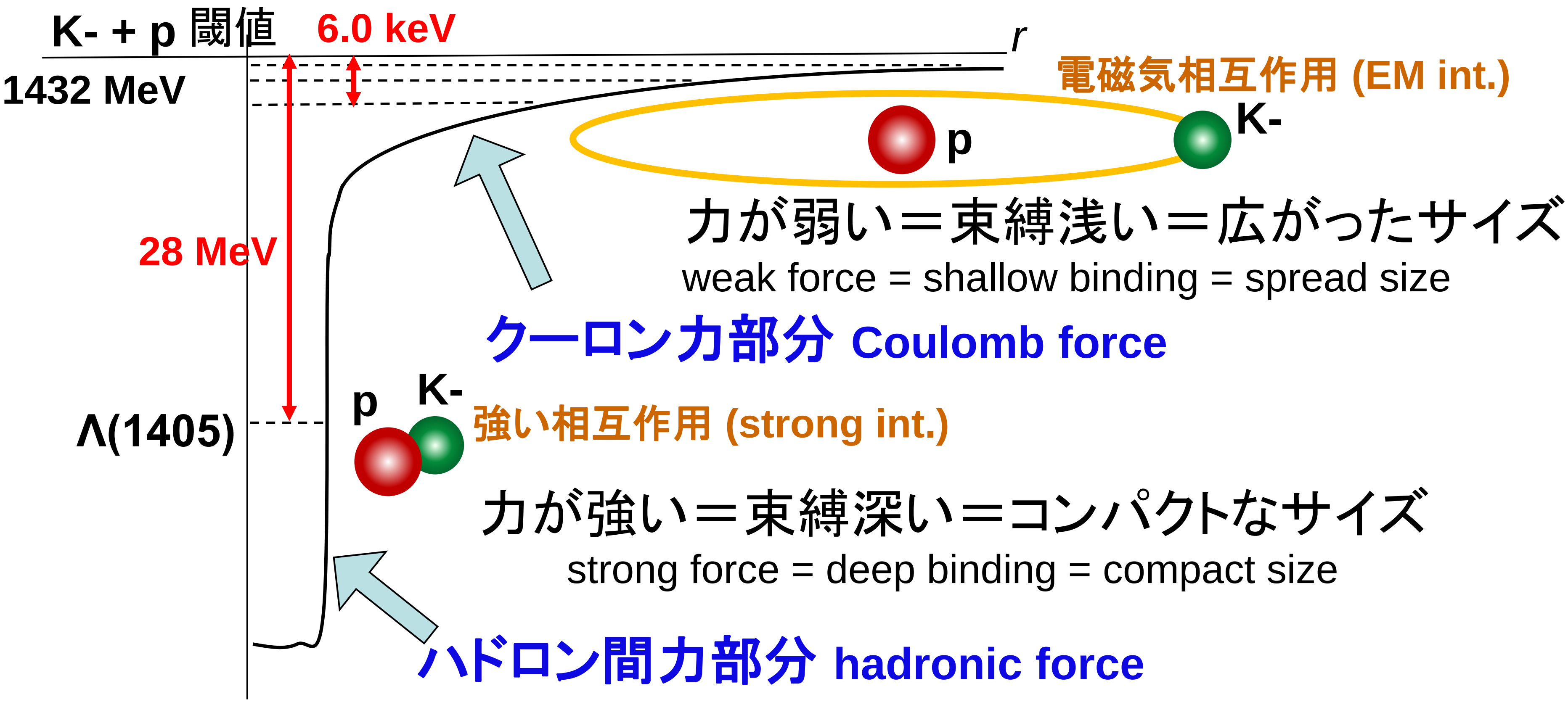
shallow potential -> small binding energy

＝＞ 構成粒子ポテンシャルでの励起エネルギーに比べて極めて小さなエネルギーしか
クラスターへの分解閾値から離れていない状態は、そのクラスターの分子的状態

State with an energy close to the cluster decay threshold should be a molecule of the clusters

異なる階層が同居する例 --Exotic atoms

Coexistence of different hierarchies



閾値近くに現れる状態は、深い状態を作るのとは異なる弱い力で形作られた（広がった）状態

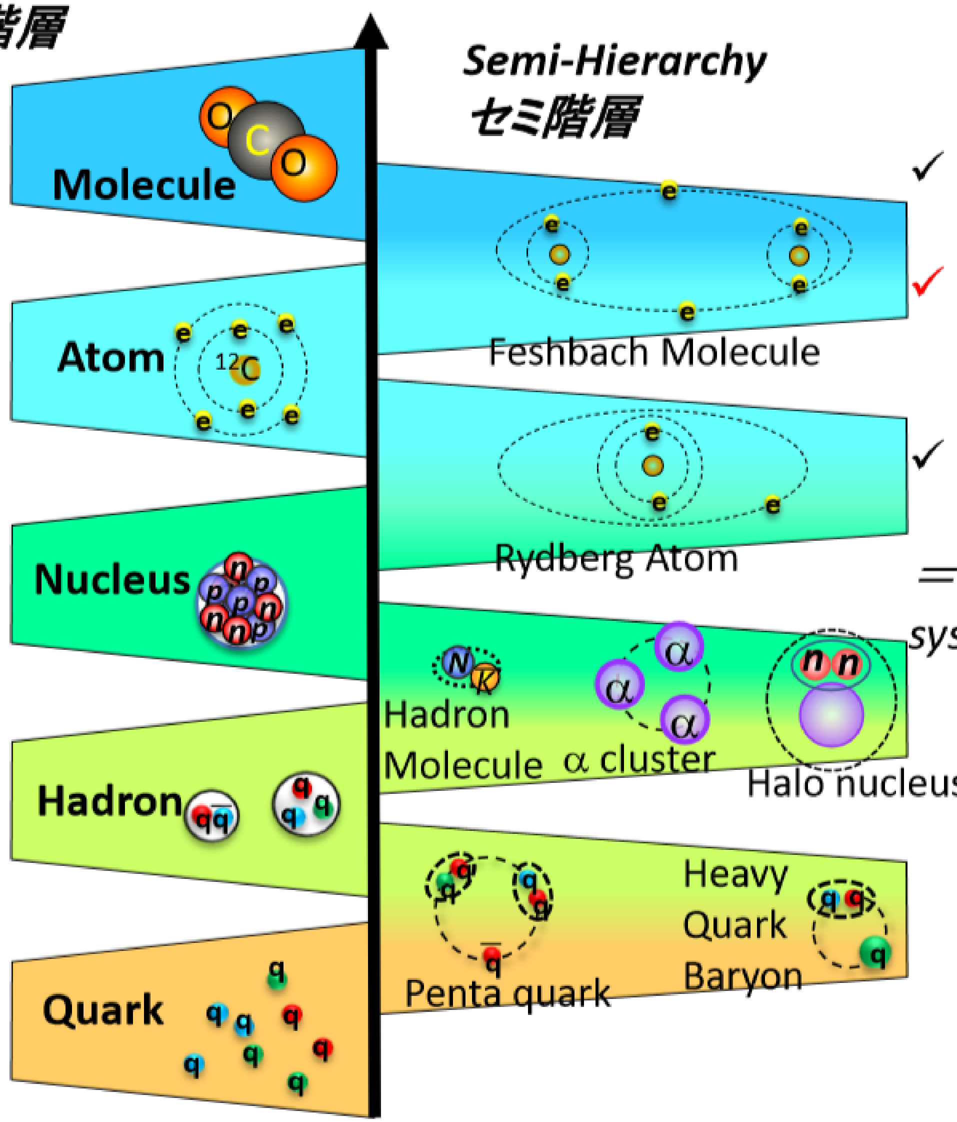
A state with an energy close to the threshold is made by a weak force different from the original force

Clusters and Semi-Hierarchy

slide by 中村隆司

Conventional Hierarchy
従来型階層

- ✓ Big Gap between Hierarchies
- ✓ **Strongly Bound 強束縛**
- ✓ Simple constituents: Nucleus= "nucleonic" system



- ✓ Smaller Gap between Hierarchies
- ✓ **Weakly Bound (Unbound) 弱束縛（弱非束縛）**
- ✓ Mixed constituents: Halo Nucleus ="nucleonic"+"dineutron" system

Semi-Hierarchy: Key Aspects to understand the hierarchical structure of matter

原子間力（共有結合の場合）はなぜできるのか

Why atom-atom force appears? (case of covalent bond)

原子間力のもと:　電子のパウリ排他律＋クーロン力

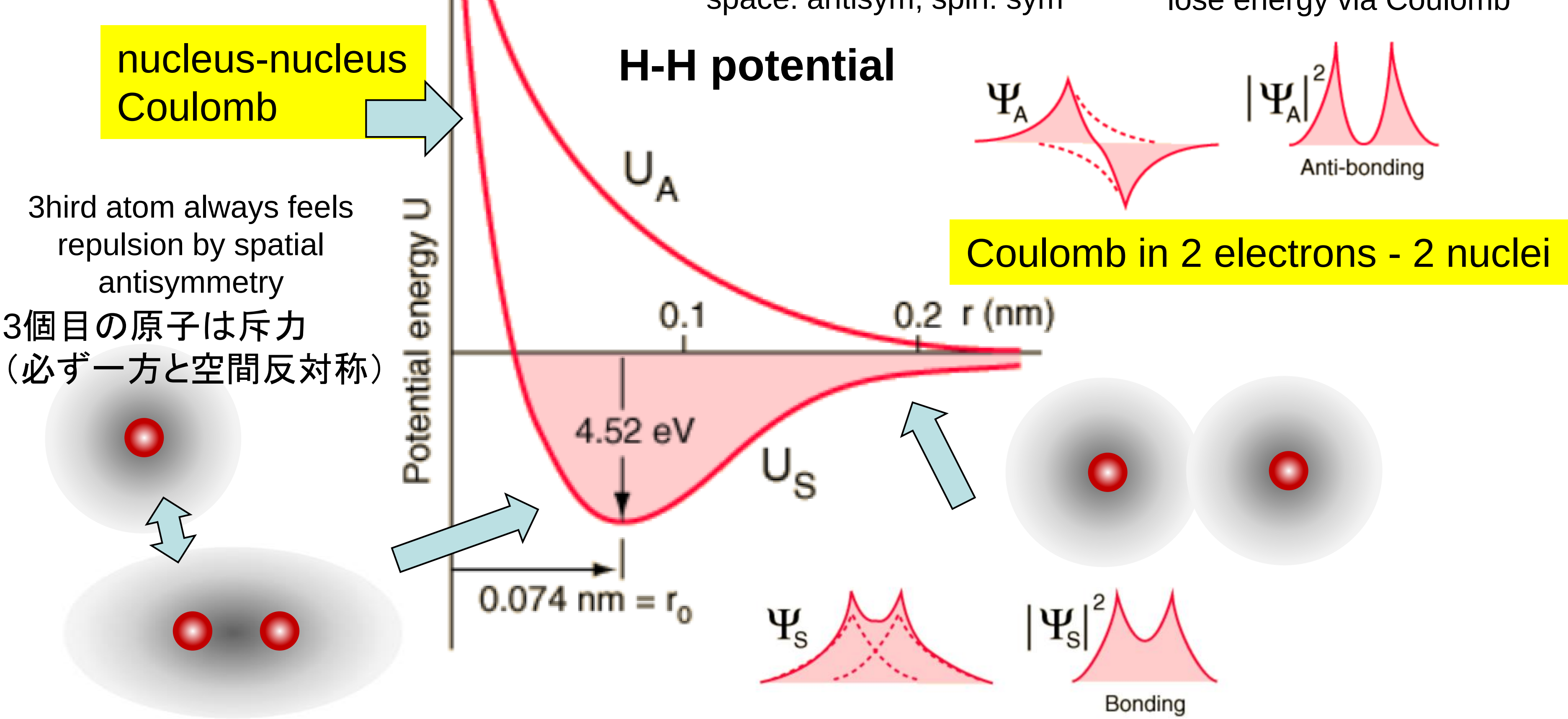
Origin of atom-atom force:　Pauli　effect of electrons and Coulomb force

space: sym; spin: antisym　　　gain energy via Coulomb

U_S(S=0）2 electron wf 空間対称（スピン反対称）→クーロンを稼ぐ

U_A(S=1）2 electron wf 空間反対称（スピン対称）→クーロンで損

space: antisym; spin: sym　　　lose energy via Coulomb



分子間力はなぜできるのか

Why molecule-molecule force appears?

分子間力のもと:　多重極電場 (高次のクーロン力)

Origin:
multipole electric force

・分子の永久分極→ 水素結合、双極子相互作用

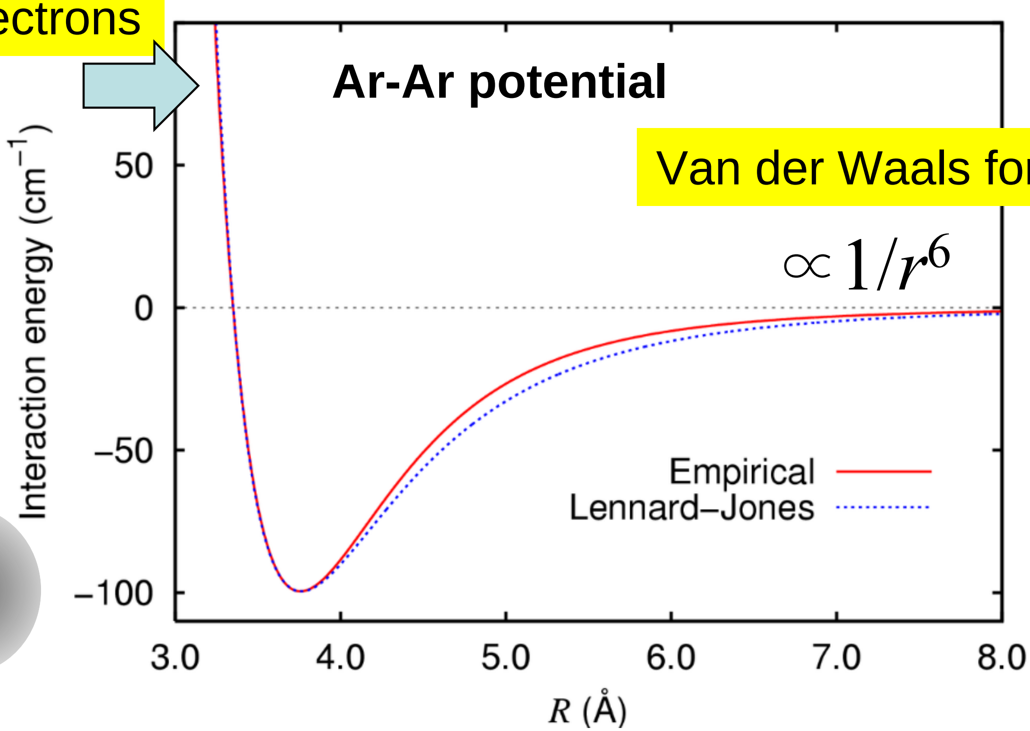
permanent polarization
-> hydrogen bond, dipole int.

・電子分布の揺らぎ＋誘起双極子（ロンドン分散力）

→ファンデルワールス力

electron fluctuation + induced dipole -> Van der Waals force

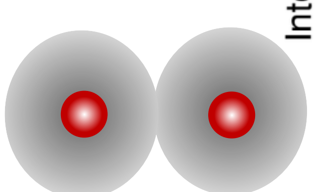
Pauli + Coulomb
between electrons

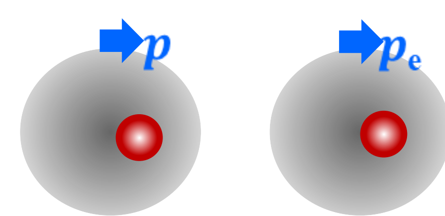


$$\boldsymbol{E} = \frac{-3(\boldsymbol{p}\cdot\hat{\boldsymbol{r}})\boldsymbol{p} + \boldsymbol{p}}{r^3}$$

$$\boldsymbol{p}_e \propto \boldsymbol{E}$$

$$U = \boldsymbol{p}_e \boldsymbol{E} \propto \frac{1}{r^6}$$





核力（バリオン間力）はなぜできるのか

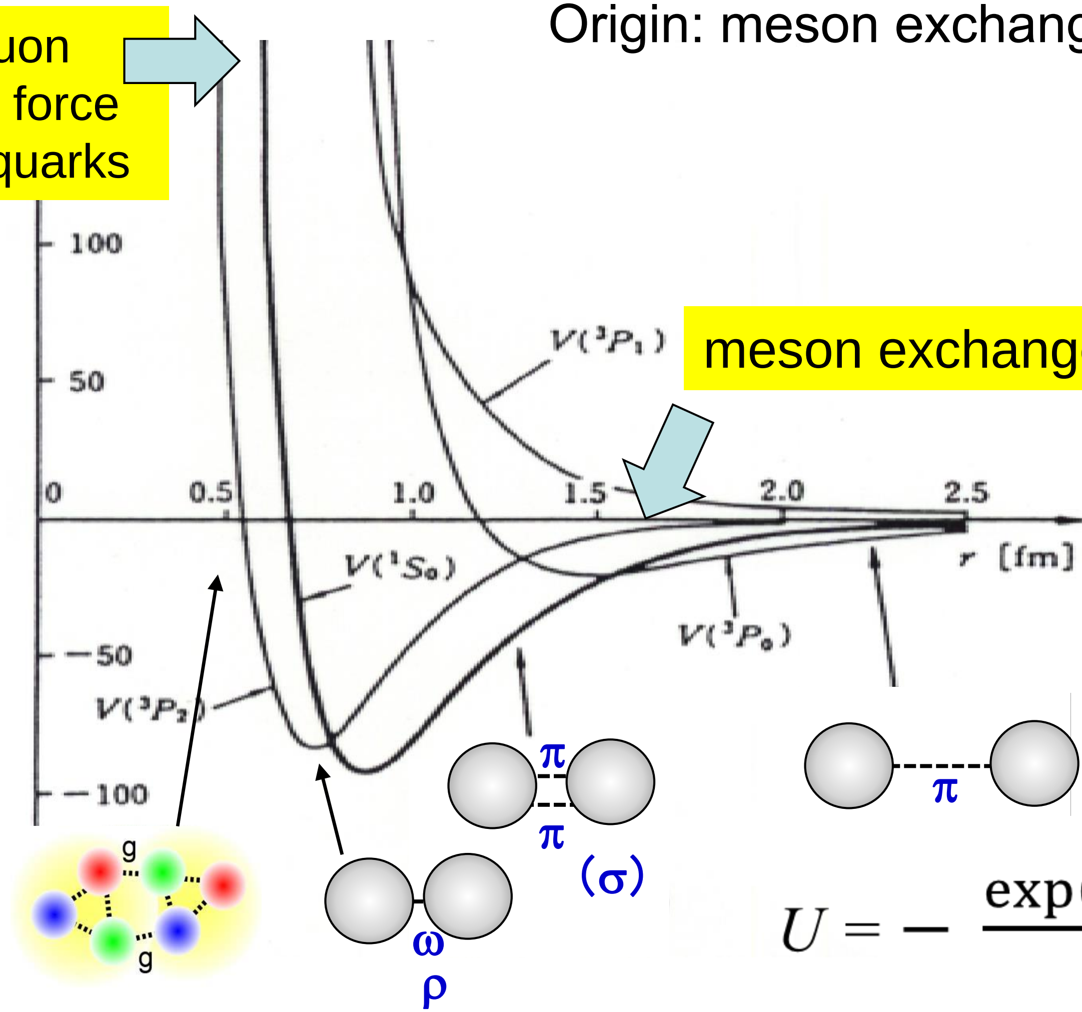
Why nuclear force(Baryon-baryon force) appears?

バリオン間力のもと:

中間子交換力（白色場） <= クォーク間力（カラー場）

Origin: meson exchange force (“white” field)

Pauli + gluon exchange force between quarks



meson exchange force

meson mass and range

中間子質量と到達距離

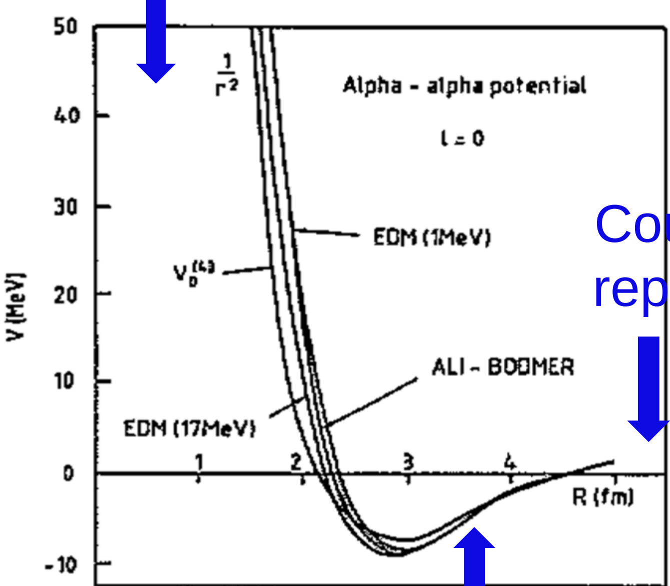
	m	$r_0 = \frac{\hbar c}{m}$
π	139 MeV	1.4 fm
η	548 MeV	0.36 fm
σ	500 MeV	0.39 fm
ρ	770 MeV	0.26 fm
ω	782 MeV	0.25 fm

$$U = -\frac{\exp(-r/r_0)}{r}, \quad r_0 = \frac{1}{m}$$

nucleus-nucleus potential

NN Pauli
Repulsive core of NN force

α–α potential

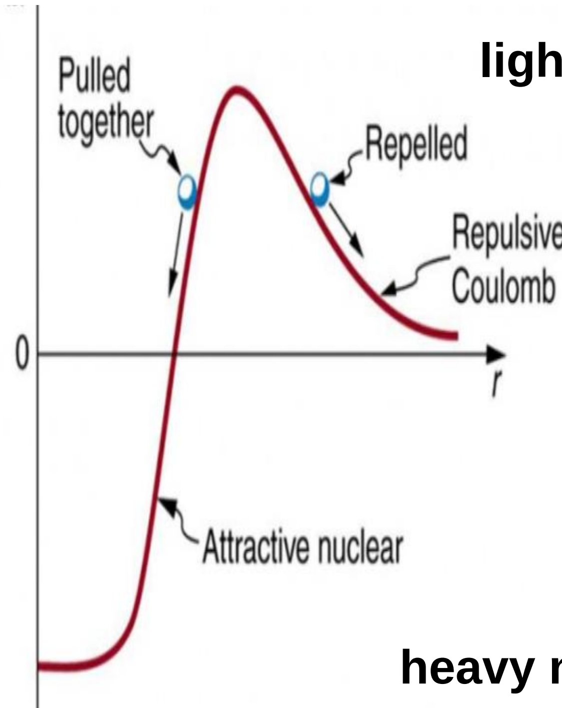


Coulomb repulsion

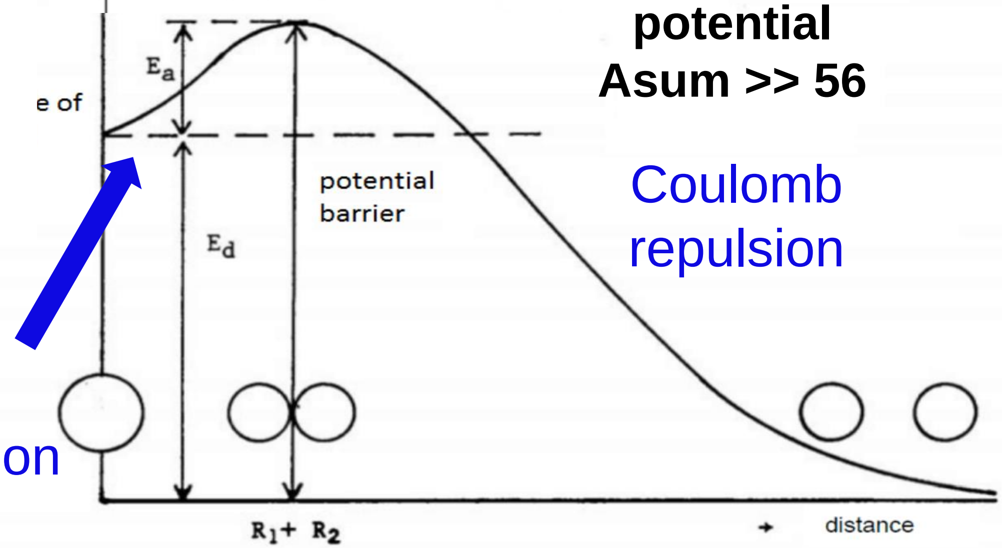
NN scalar force

Coulomb + nuclear attraction

light nucleus-nucleus potential
Asum << 56



heavy nucleus-nucleus potential
Asum >> 56



Coulomb repulsion

Origin of cluster-cluster force

これがあると高次のクラスター（次の階層）ができる

これがあるとクラスターが安定化

Cluser (Element)	force inside cluster charge saturation	cluster-cluster force small r repulsion	large r attraction
hadron (nucleon) (quark)	gluon exch. force （color exch.) color= 0(white）	gluon exch. force q-q Pauli repulsion	meson(color=0) exch.
α particle (nucleon N)	nuclear(NN) force (tensor force) spin-isospin=0	repulsive core of NN force N-N Pauli repulsion	Scalar part of NN force（+Coulomb repulsion）
(heavy)nucleus (N(hadron), α)	nuclear force Coulomb force	Coulomb repulsion （attractive nuclear force at very small r）	--
atom （electron, nucleus）	Coulomb force electric charge=0	e-e Coulomb repulsion e-e Pauli repulsion	el-nucleus Coulomb attraction (electron exch. force)
molecule （incl.monoatomic molecule ）（atom）	Electric force （+e exch. force） electric charge=0 e spin=0	e-e Coulomb repulsion e-e Pauli repulsion	multipole electric force（Van der Waals force）

まとめ：階層の起源は？

Summary: origin of hierarchy?

Step 1

・少数の要素が強い力で固く結合し“クラスター”ができる。
・要素のある特定の個数や組み合わせで力荷が飽和する。

A few elements are tightly bound via strong force.
With a specific number of elements, the charge of the strong force (partly) saturates.

・クラスター間に近距離では強い斥力がある

Strong repulsion exists between the clusters

→ クラスターの安定性が保証される　Stability of the cluster

Step 2

・クラスター間に弱い引力がある　weak attraction between clusters

→ クラスター同士が緩く集合して次の階層が生まれる

-> サイズも大きくなる

Clusters are loosely bound and the next hierarchy appears.

バリオン間力の起源
Origin of baryon-baryon interactions

核力（バリオン間力）はなぜできるのか

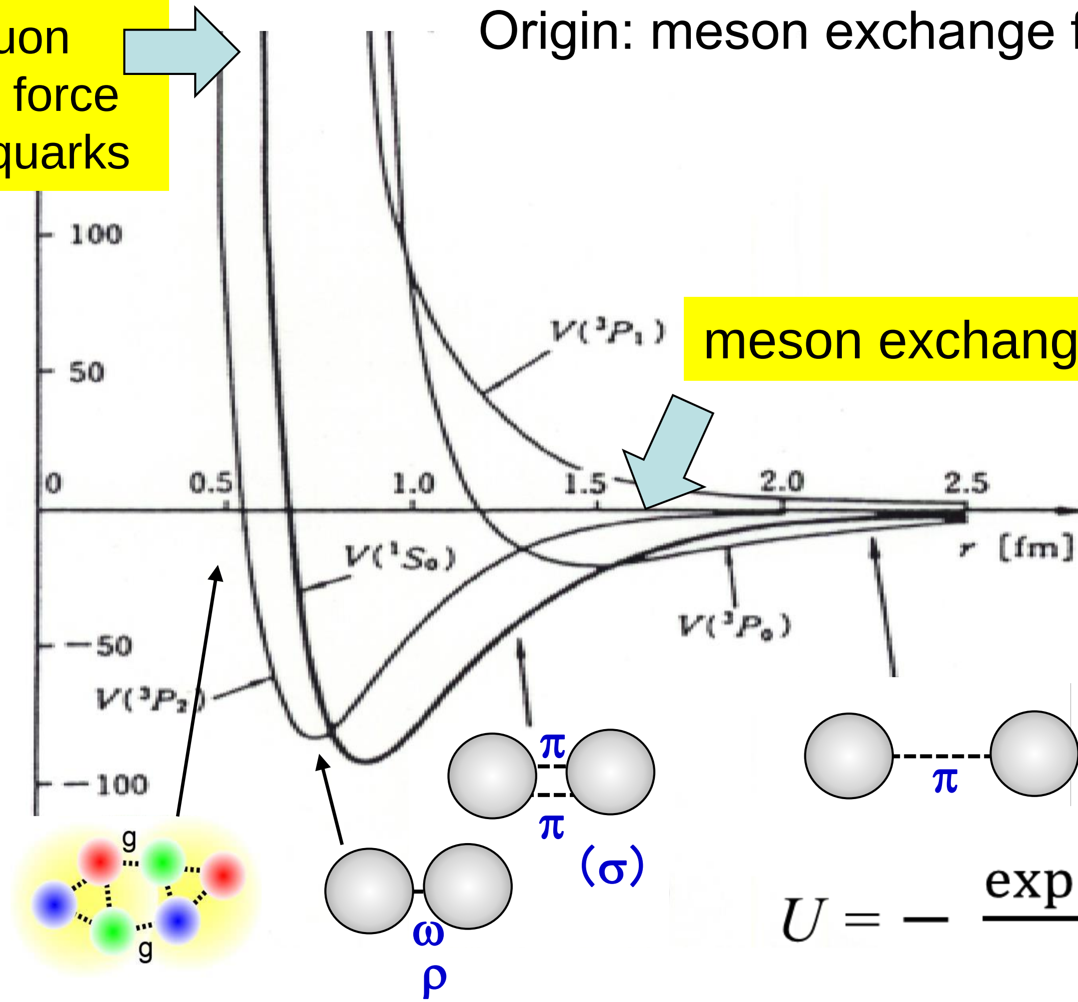
Why nuclear force(Baryon-baryon force) appears?

バリオン間力のもと:

中間子交換力（白色場） <= クォーク間力（カラー場）

Pauli + gluon exchange force between quarks

Origin: meson exchange force (“white” field)



meson mass and range

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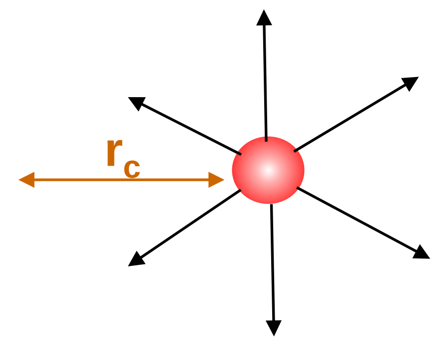
$$U = -\frac{\exp(-r/r_0)}{r}, \quad r_0 = \frac{1}{m}$$

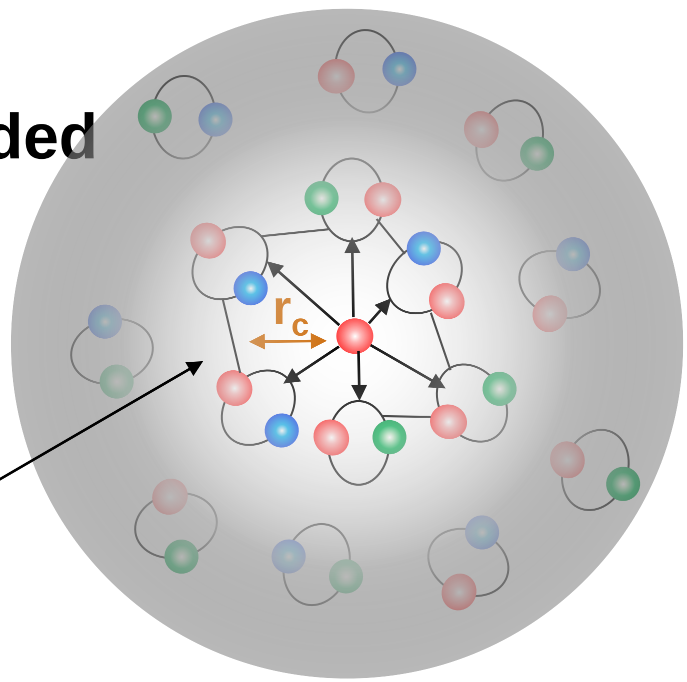
Image of strong interaction

- $r < r_c$ confinement scale (~0.5 fm)
  gluon exchange (color field), 1/r
  symmetry of quarks (Pauli effect)



- $r > r_c$ confinement scale (~0.5 fm)
  gluon filed is shielded
  qq^{bar}(white)＝"meson" is not shielded

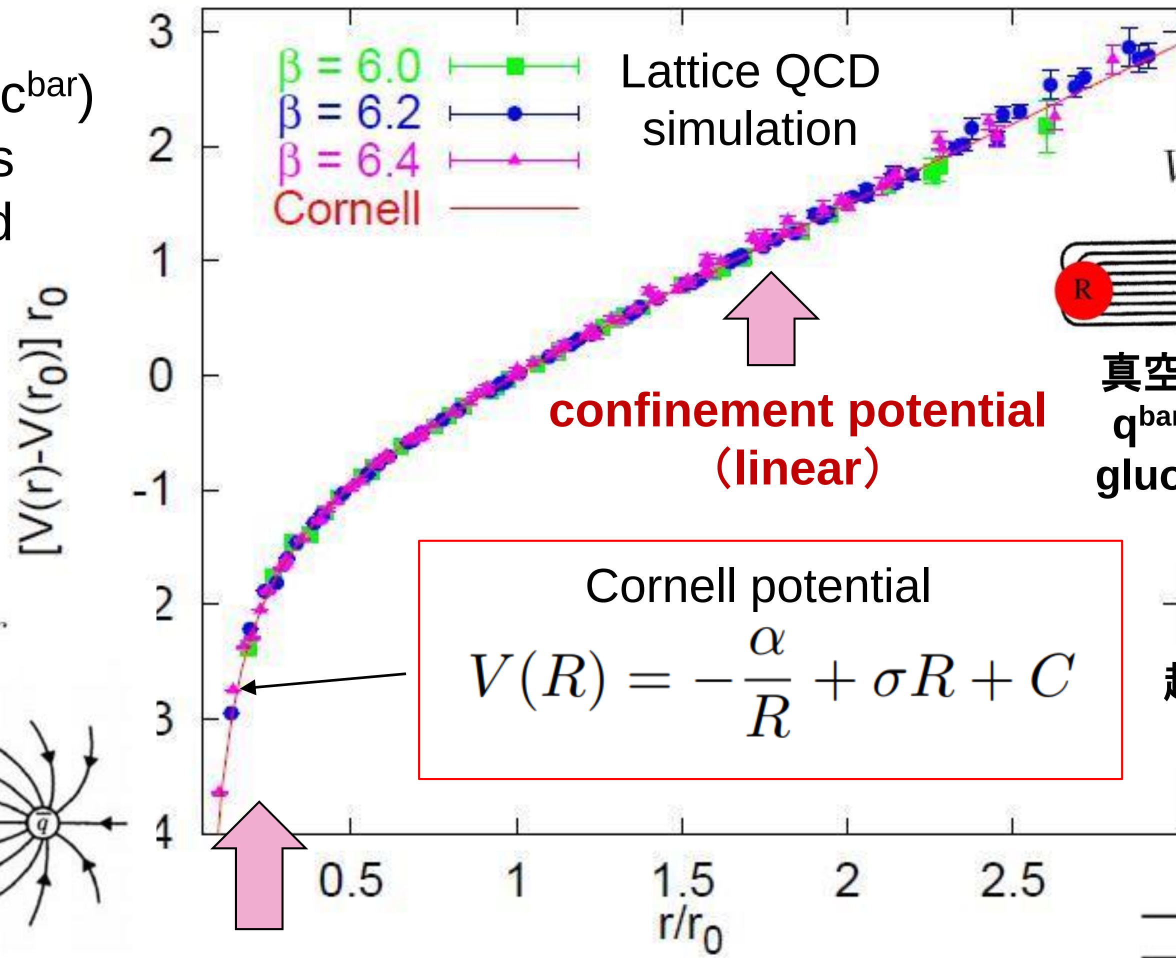
constituent quark
the region where the color of the valence quark can propagate



q $\bar{q}$ potential

qq potential in a baryon
$V_{qq} = \frac{1}{2} V_{q\bar{q}}$

charmonium($c\bar{c}$) spectrum is reproduced

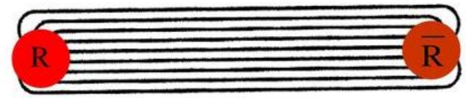


confinement potential
(linear)

Cornell potential

$$V(R) = -\frac{\alpha}{R} + \sigma R + C$$

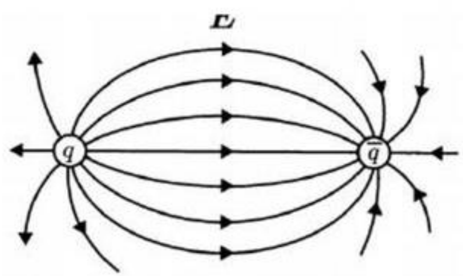
$V(r) \cong \sigma r$



真空中に凝縮している
$q^{bar}q$対に遮蔽されて
gluonが四方八方には
飛べない

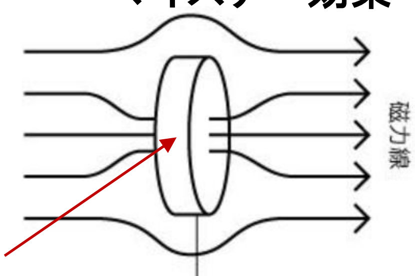
超伝導体中の磁束
と似ている

$V(r) = -C\alpha/r$



Coulomb type
gluon (mass=0) exchange
=> exp(-mr)/r = 1/r
(same as photon exchange)

マイスナー効果



常伝導部分
磁束のピン止め

超伝導体

核力の性質(properties of nuclear force)

核力 nuclear force

- 有限の到達距離　～数 fm
  finite range ~ a few fm
- 短距離(r<0.5fm)の強い斥力
  strong repulsion at short distance
- 荷電交換力、アイソスピン依存性あり
  charge exchange force, isospin dependence.
- スピン依存性大
  Large spin dependence
  - 大きなテンソル力
    Large tensor force
  - 大きな LS力
    Large LS force
- 3体力がある 3-body force exists

陽子・電子間の電磁気力

EM force between p and e-

- 無限大の到達距離　U∝1/r
  infinite range
- 引力のみ
  Attraction only
- 荷電交換なし
  No charge exchange
- スピン依存性小
  Small spin dependence
  - 小さなテンソル力($\mu_e\mu_p$ -> hf splitting)
    Small LS force
  - 小さなLS力($\mu_e H_p$ -> fine splitting)
    Small LS force
- 3体力なし
  No 3-body force

pion(π^+, π^0, π^-) exchange can explain them

中心力 $$V_0(r) + V_\sigma(r)\,\sigma_1\cdot\sigma_2 + V_\tau(r)\,\tau_1\cdot\tau_2 + V_{\sigma\tau}(r)\,(\sigma_1\cdot\sigma_2)(\tau_1\cdot\tau_2)$$

テンソル力 $$+\,V_T S_{12} + V_{T\tau} S_{12}\tau_1\cdot\tau_2$$

$$S_{12} = \frac{3}{r^2}(\boldsymbol{\sigma}_1\cdot\mathbf{r})(\boldsymbol{\sigma}_2\cdot\mathbf{r}) - (\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)$$

LS力 $$+\,V_{LS} L\cdot S + V_{LS\tau}(L\cdot S)(\tau_1\cdot\tau_2) + \ldots$$

One pion exchange potential (OPEP)

Similar to interaction between two magnetic dipole moments

$$V = -\boldsymbol{\mu}_1 \boldsymbol{H}_2 = -(\boldsymbol{\mu}_1 \boldsymbol{\nabla})(\boldsymbol{\mu}_2 \boldsymbol{\nabla})(1/r)$$

Pseudo scalar field with mass m_π

$$V_{\mathrm{OPE}}(\mathbf{r}) = -\left(\frac{f}{m_\pi}\right)(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\nabla})(\boldsymbol{\sigma}_2 \cdot \boldsymbol{\nabla}) \frac{1}{4\pi}\frac{e^{-m_\pi r}}{r}$$

$$= -\frac{1}{3}\frac{1}{4\pi} f^2 m_\pi (\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)\left[(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) + \left(m_\pi^2 + \frac{3m_\pi}{r} + \frac{3}{r^2}\right) S_{12}\right] \frac{e^{-m_\pi r}}{r}$$

$$S_{12} = \frac{3}{r^2}(\boldsymbol{\sigma}_1 \cdot \mathbf{r})(\boldsymbol{\sigma}_2 \cdot \mathbf{r}) - (\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)$$

Agrees very well with the central + tensor parts of the nuclear force for r >2 fm

How about shorter regions?

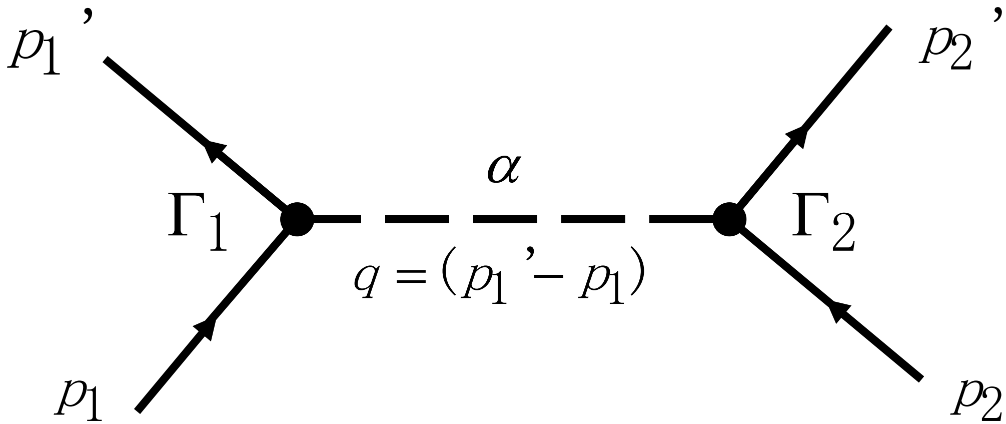
Introduce more mesons with heavier masses → shorter ranges of force

Coupling constant f <= Assumed to be the same via SU(3)f symmetry

Meson exchange models (OBE models)

from Machleidt's lecture

Feynman diagram for NN scattering



$$\text{Amplitude: } F_\alpha(p', p) = \frac{\bar{u}_1' \Gamma_1 u_1 \, P_\alpha \, \bar{u}_2' \Gamma_2 u_2}{q^2 - m_\alpha^2}$$

with Dirac spinor $u(p,s) = \sqrt{\frac{E+M}{2M}} \begin{pmatrix} \chi_s \\ \frac{\vec{\sigma} \cdot \vec{p}}{E+M} \chi_s \end{pmatrix} \approx \begin{pmatrix} \chi_s \\ \frac{\vec{\sigma} \cdot \vec{p}}{E+M} \chi_s \end{pmatrix} \approx \begin{pmatrix} \chi_s \\ 0 \end{pmatrix}$

where $E = \sqrt{\vec{p}^2 + M^2}$ and χ_s is a two-component Pauli spinor.

from Machleidt's lecture

Pseudo-vector coupling of a pseudo-scalar meson

Lagrangian:

$$\mathcal{L}_{\pi NN} = -\frac{f_{\pi NN}}{m_\pi} \bar{\psi} \gamma^\mu \gamma_5 \vec{\tau} \psi \cdot \partial_\mu \vec{\varphi}^{(\pi)}$$

Vertex: i **times the Lagrangian stripped off the fields (for an incoming pion)**

$$\Gamma_{\pi NN} = (i)^2 \frac{f_{\pi NN}}{m_\pi} \gamma^\mu \gamma_5 \vec{\tau}\, q_\mu \approx \frac{f_{\pi NN}}{m_\pi} (\vec{\sigma} \cdot \vec{q}) \vec{\tau}$$

Potential: i **times**

$$(P_\pi = i,\ q^2 \approx -\vec{q}^{\,2})$$

the amplitude

$$V_\pi = iF_\pi \approx -\frac{f_{\pi NN}^2}{m_\pi^2} \frac{(\vec{\sigma}_1 \cdot \vec{q})(\vec{\sigma}_2 \cdot \vec{q})}{\vec{q}^{\,2} + m_\pi^2} \vec{\tau}_1 \cdot \vec{\tau}_2$$

from Machleidt's lecture

Pseudo-vector coupling of a pseudo-scalar meson, cont'd

Using the operator identity

$$(\vec{\sigma}_1 \cdot \vec{q})(\vec{\sigma}_2 \cdot \vec{q}) = \frac{\vec{q}^{\,2}}{3}\left[\vec{\sigma}_1 \cdot \vec{\sigma}_2 + S_{12}(\hat{q})\right]$$

with $S_{12}(\hat{q}) \equiv 3(\vec{\sigma}_1 \cdot \hat{q})(\vec{\sigma}_2 \cdot \hat{q}) - \vec{\sigma}_1 \cdot \vec{\sigma}_2$ **("Tensor operator"),**

the one-pion exchange potential (OPEP) can be written as

$$V_\pi = \frac{f_{\pi NN}^2}{3m_\pi^2} \frac{\vec{q}^{\,2}}{\vec{q}^{\,2} + m_\pi^2}\left[-\vec{\sigma}_1 \cdot \vec{\sigma}_2 - S_{12}(\hat{q})\right] \vec{\tau}_1 \cdot \vec{\tau}_2$$

from Machleidt's lecture

Meson exchange models (OBE models)

pseudoscalar meson (I=1)

$\pi(138)$

$$V_\pi = \frac{f_{\pi NN}^2}{3m_\pi^2}\frac{\vec{q}^{\,2}}{\vec{q}^{\,2}+m_\pi^2}\left[-\vec{\sigma}_1\cdot\vec{\sigma}_2 - S_{12}(\hat{q})\right]\vec{\tau}_1\cdot\vec{\tau}_2$$

Long-ranged attractive tensor force

scalar meson

$\sigma(600)$

$$V_\sigma \approx \frac{g_\sigma^2}{\vec{q}^{\,2}+m_\sigma^2}\left[-1 - \frac{\vec{L}\cdot\vec{S}}{2M^2}\right]$$

intermediate-ranged, attractive central force plus LS force

vector meson (I=0)

$\omega(782)$

$$V_\omega \approx \frac{g_\omega^2}{\vec{q}^{\,2}+m_\omega^2}\left[+1 - 3\frac{\vec{L}\cdot\vec{S}}{2M^2}\right]$$

vector coupling only

short-ranged, repulsive central force plus strong LS force

vector meson (I=1)

$\rho(770)$

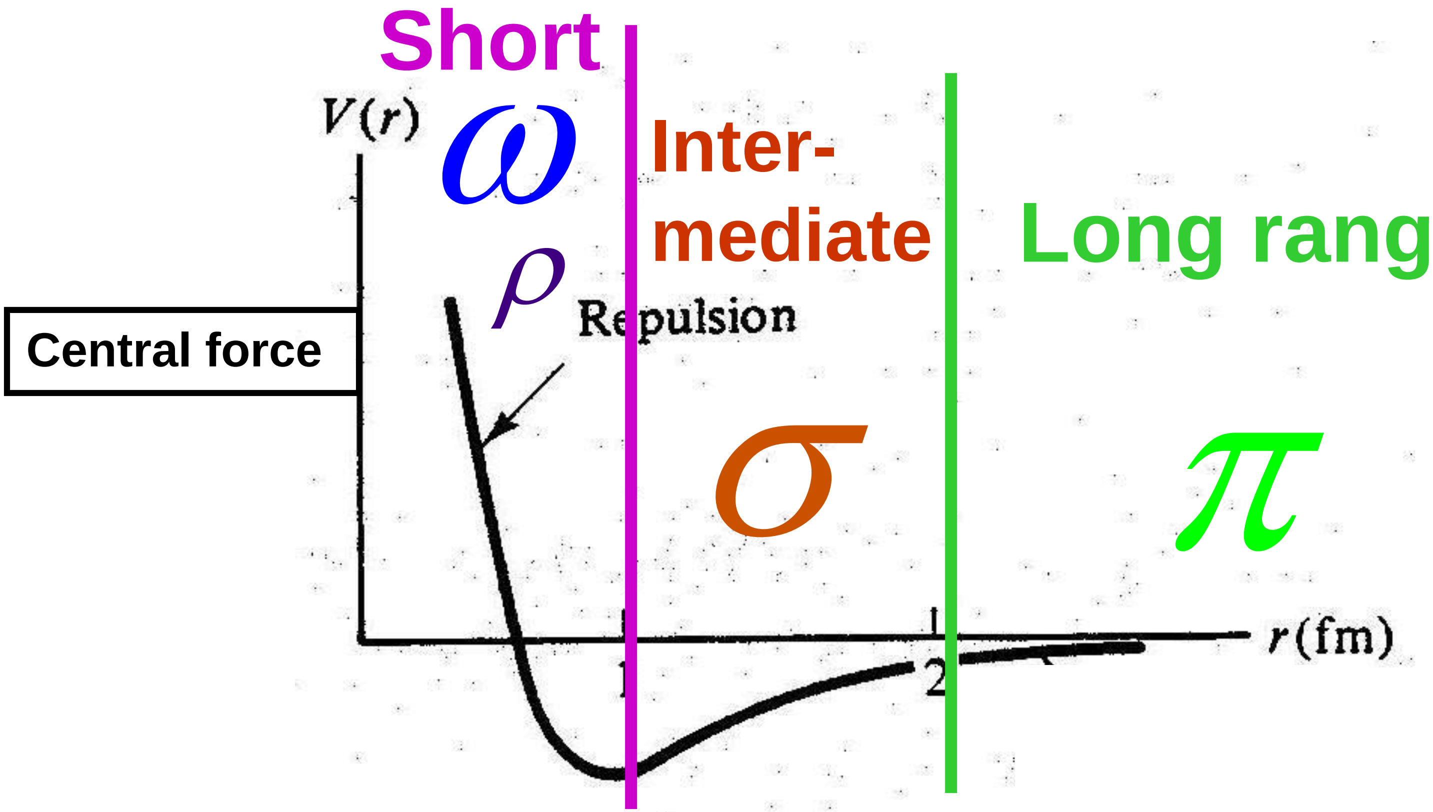
$$V\rho = \frac{f_\rho^2}{12M^2}\frac{\vec{q}^{\,2}}{\vec{q}^{\,2}+m_\rho^2}\left[-2\vec{\sigma}_1\cdot\vec{\sigma}_2 + S_{12}(\hat{q})\right]\vec{\tau}_1\cdot\vec{\tau}_2$$

tensor coupling only

short-ranged tensor force, opposite to pion

from Machleidt's lecture

Summary: Most important parts of the nuclear force



Tensor force π ρ

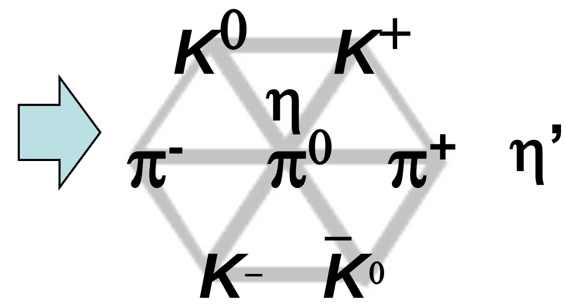
Spin-orbit force ω σ

OBE models: extension to SU(3)$_f$

pseudoscalar meson

$\pi(138)$

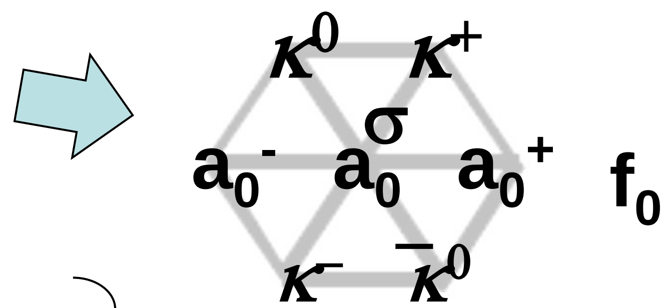
$$V_\pi = \frac{f_{\pi NN}^2}{3m_\pi^2}\frac{\vec{q}^2}{\vec{q}^2+m_\pi^2}\left[-\vec{\sigma}_1\cdot\vec{\sigma}_2 - S_{12}(\hat{q})\right]\vec{\tau}_1\cdot\vec{\tau}_2$$



scalar meson

$\sigma(600)$

$$V_\sigma \approx \frac{g_\sigma^2}{\vec{q}^2+m_\sigma^2}\left[-1-\frac{\vec{L}\cdot\vec{S}}{2M^2}\right]$$



vector meson (I=0)

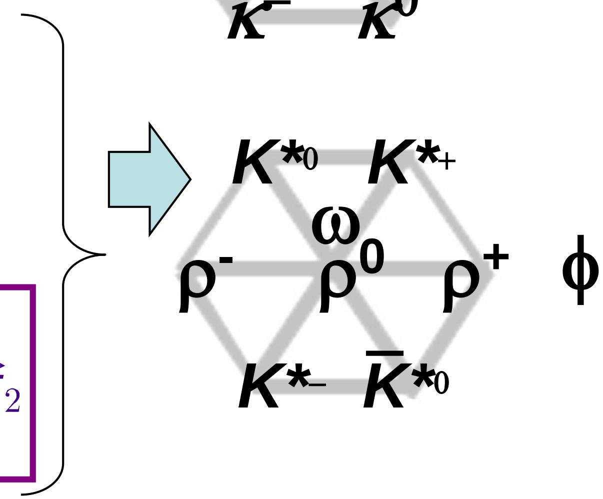
$\omega(782)$

$$V_\omega \approx \frac{g_\omega^2}{\vec{q}^2+m_\omega^2}\left[+1-3\frac{\vec{L}\cdot\vec{S}}{2M^2}\right]$$

vector meson (I=1)

$\rho(770)$

$$V\rho = \frac{f_\rho^2}{12M^2}\frac{\vec{q}^2}{\vec{q}^2+m_\rho^2}\left[-2\vec{\sigma}_1\cdot\vec{\sigma}_2 + S_{12}(\hat{q})\right]\vec{\tau}_1\cdot\vec{\tau}_2$$



Coupling constant is assumed to be universal for the same multiplet

核力（バリオン間力）の疑問

questions in nuclear force (BB forces)

- 短距離部分（斥力芯）は具体的にどう理解すべきか？
  QCM描像“クォーク間パウリ効果＋グルオン交換力”は、正しく十分なのか？

  How should we understand the short range repulsion?
  Pauli effect + gluon exchange (QCM picture) is correct and enough?

- “重い中間子の交換”の描像は正しいか？ 中間子交換力との切り分けは？

  Picture of “heavy meson exchange” correct?
  How to separate between meson picture and quark picture?

- 3体力、とくに短距離3体斥力はどんなもので, どう理解すべきか。

  What is 3-body force and how should we understand it?

- 原子核を作る核力は、強い斥力と強い引力がキャンセルして残る弱い引力:
  他のバリオンでも共通か、偶然か？

  Cancellation of strong attraction and repulsion in nuclear force:
  Is it accidental? How about for the other BB interactions?

<u>解明の手がかり:核力→バリオン間力への拡張</u>

Key: Extension of Nuclear force to BB forces

- $m_{u,d}$~300 MeV, m_s~500 MeV ～ SU(3)$_f$ symmetry

  質量の違いの効果が小さい一理論的に扱い易い

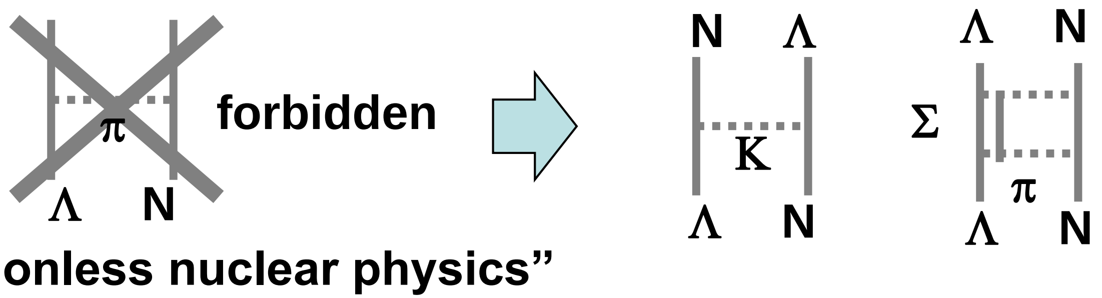
  Small effect from mass difference– theoretically easier

  核力は s quarkを入れると (NN->YN, YYで）どう変化するか

  How does nuclear force change by s quark?

- 交換される中間子が違う —> 中間子交換模型の検証

  Exchanged mesons are different –> test of meson exc. picture



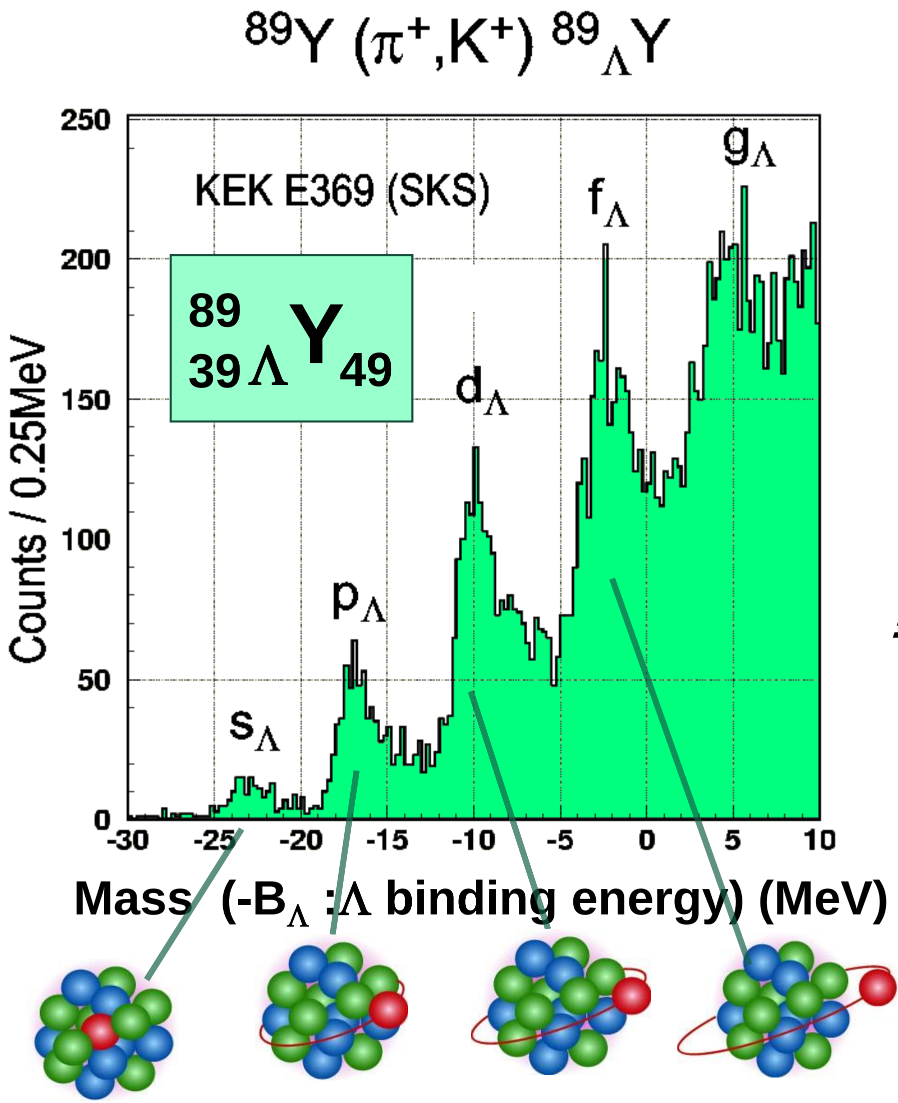
- 短距離核力のクォーク自由度を、異なるクォークで明らかにする

  Quark degree of freedom in the short rage force can be clarified via s quark

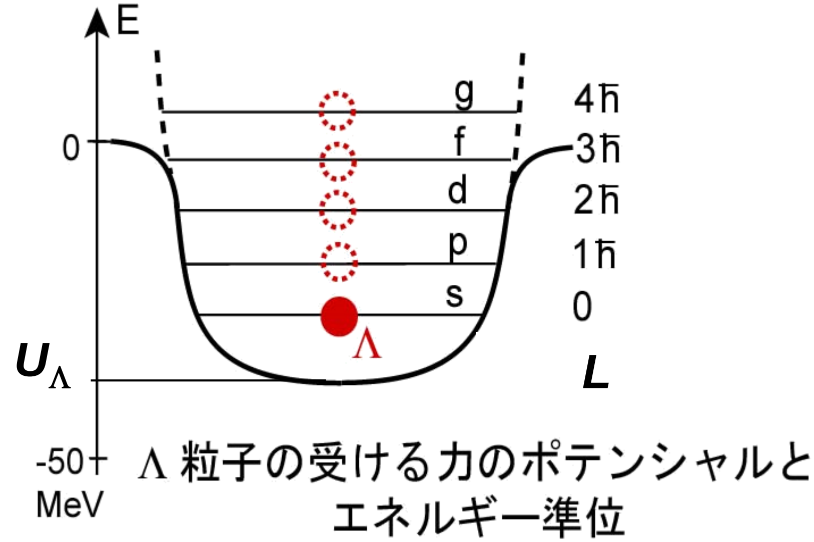
  引力芯、極めて強い斥力芯、 などの出現？

  Appearance of attractive core, extremely repulsive core?

Λ hypernuclei and ΛN interaction



Hotchi et al., PRC 64 (2001) 044302



=>

U_Λ (Λ's potential depth) = - 30 MeV

c.f. U_N = - 50 MeV

ΛN force is attractive, slightly weaker than NN force.

=> Λ should appear inside neutron stars via n -> Λ

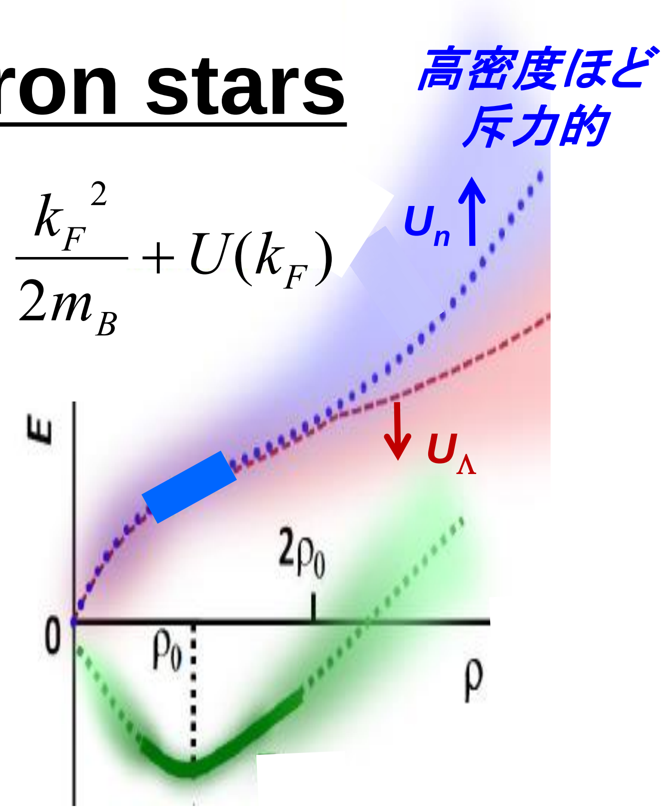
Λ appearance in neutron stars

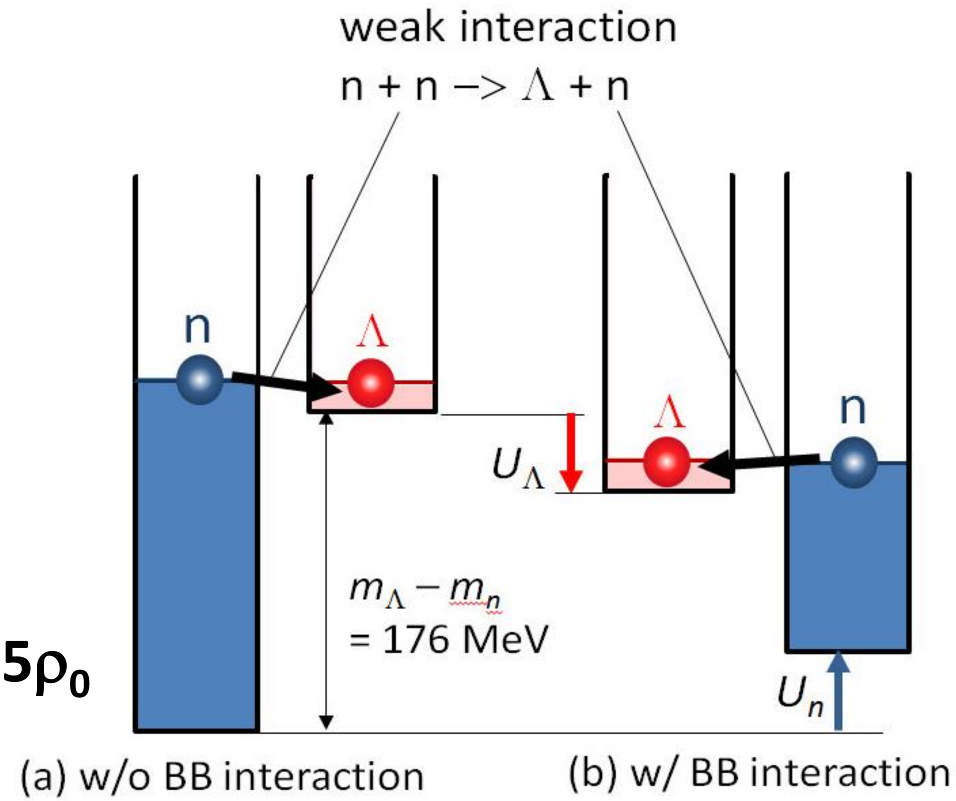
Fermi gas model

$$p_F = (3\pi^2 \rho_n)^{1/3}$$

$$E_F = \frac{p_F^2}{2m_n} > m_\Lambda - m_n \longrightarrow \rho_n > 5.0\rho_0$$

$$\mu_B = m_B + \frac{k_F{}^2}{2m_B} + U(k_F)$$





$\rho \sim 5\rho_0$

U_Λ = - 30 MeV at ρ_0

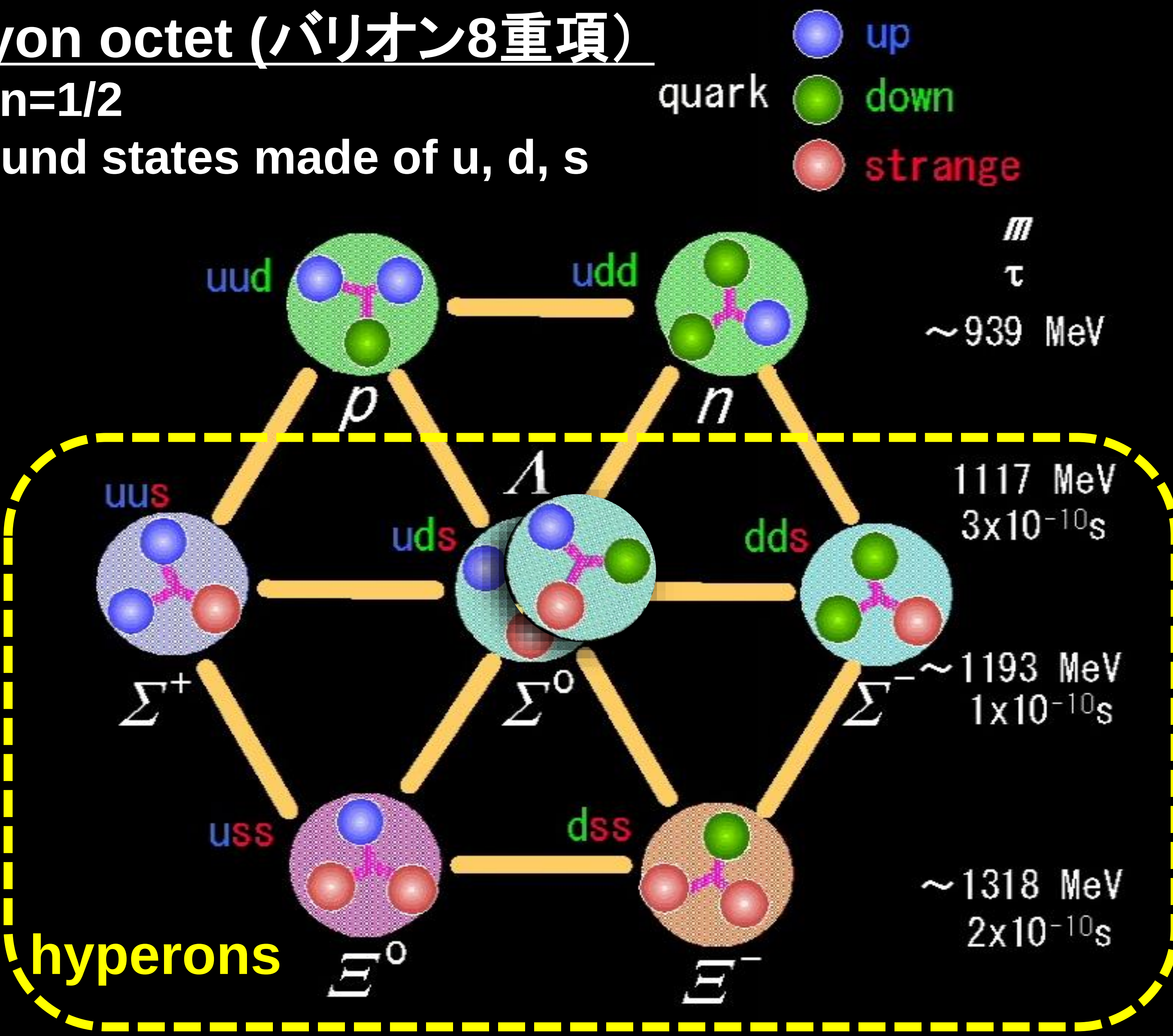
U_n > 0 at large ρ

Λ appears at $\rho \sim 2 - 2.5\rho_0$

Baryon octet (バリオン8重項)

spin=1/2

ground states made of u, d, s



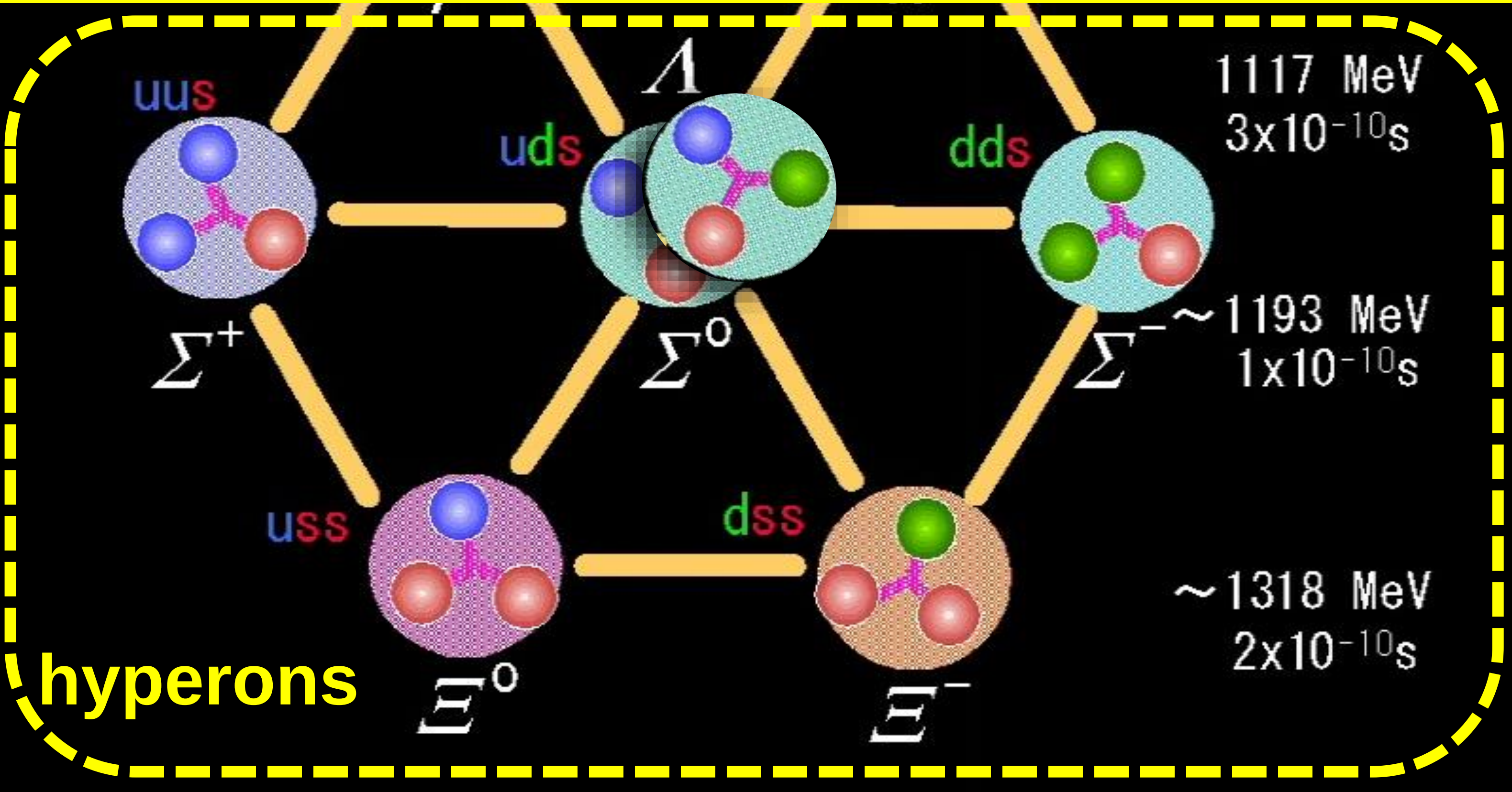
Lifetime of hyperons(Y) ~10^{-10} sec

-> decay at ~10^{-10} s x 3×10^8 m/s = 3 cm

=> Scattering experiment very difficult

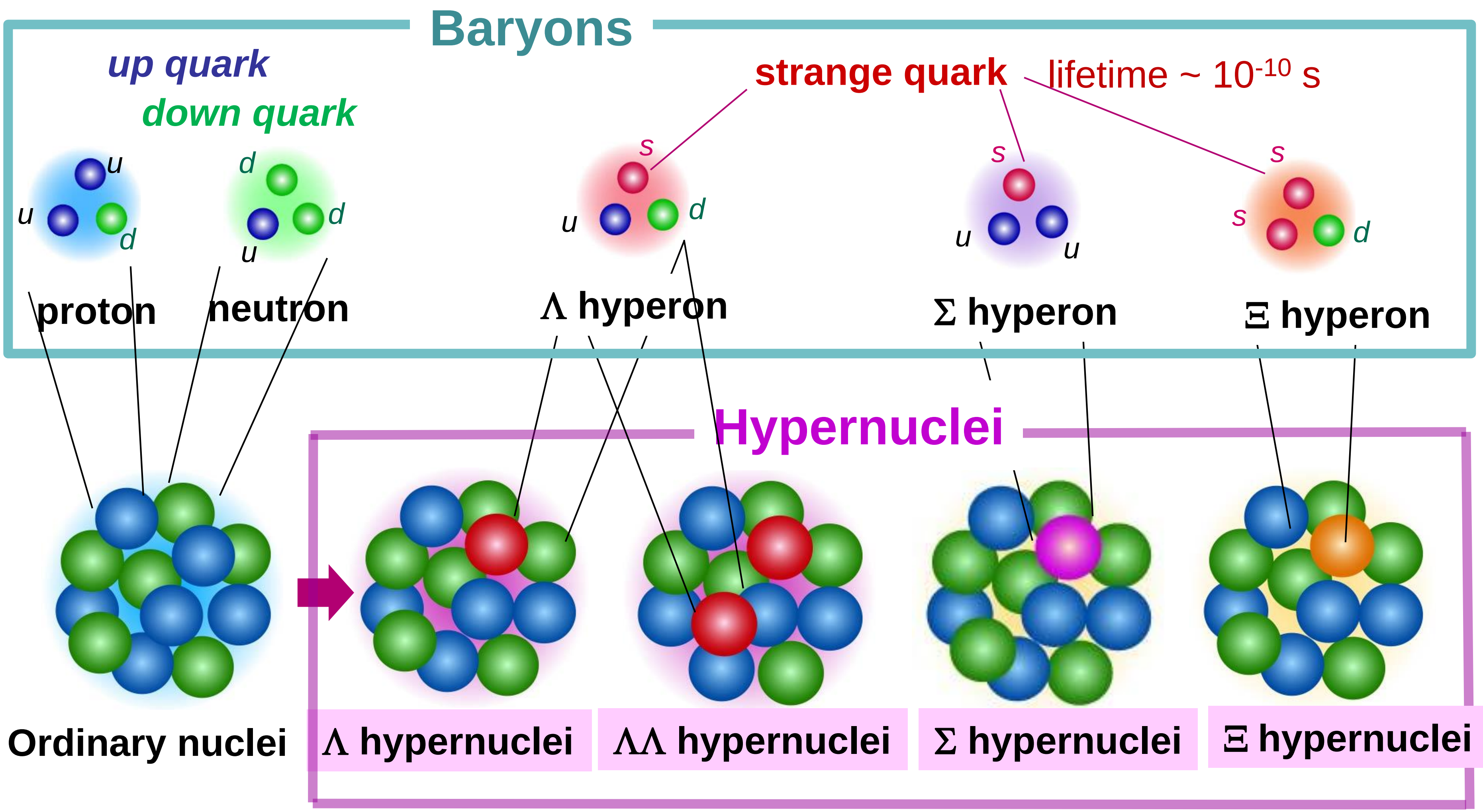
寿命が短すぎて YN散乱実験は困難

-> Put them into a nucleus 原子核に入れてエネルギーを調べる



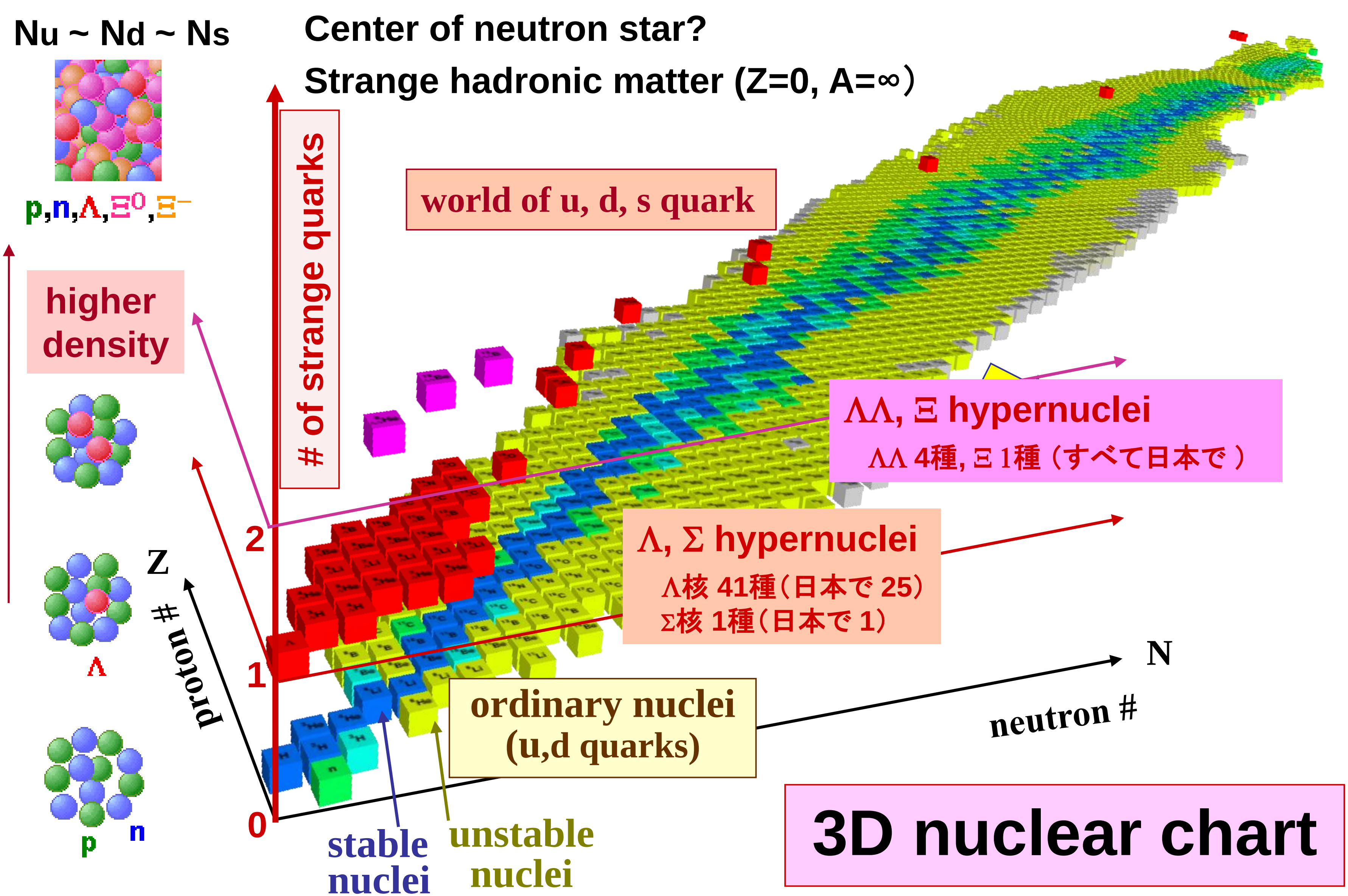
Hypernuclei

Atomic Nucleus (= protons + neutrons) => baryon many-body systems



They can be produced with high energy accelerators.

World of matter with strangeness

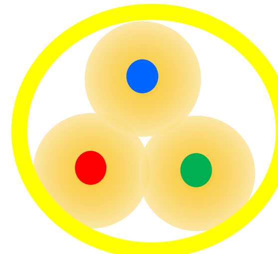


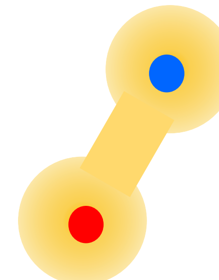
Experimental status of BB interactions

	scattering data	correlation data	Nuclei/ Hypernuclei
NN	◎	○	・Saturation point of nucl. matter： (a_V , , ρ_0) ・Plenty of nuclear data <- NN scat. data
ΛN	△ Low stat. Limited p No pol. obs.	△ attractive	・$^{3}_{\Lambda}$H to $^{208}_{\Lambda}$Pb -> U_Λ＝-30 MeV ・A≦16 Level data -> small spin-spin, spin-orbit, tensor forces
ΣN	△ Low stat. Limited p No pol. obs.	×	・$^{4}_{\Sigma}$He (0^+) bound state -> Large spin-isospin dependence ・Σ+^{28}Si spectra -> U_Σ ～ +30 MeV ・Σ atom X-rays
ΞN	×	△ attractive	・$^{14}_{\Xi}$C bound state (Kiso): B_Ξ ~ 1 MeV (attractive)
ΛΛ	×	△ attractive	・$^{6}_{\Lambda\Lambda}$He（Nagara) : $\Delta B_{\Lambda\Lambda}$=0.6 MeV (weakly attractive)

Oka-Yazaki's Quark Cluster Model

Effect of short range force





- **Constituent quark**

  $m_{u,d} \sim 300$ MeV, $m_s \sim 500$ MeV

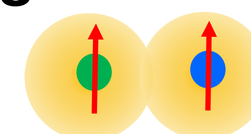
- **Confinement potential**

$$V_{12}(r) = -\Sigma_a (\lambda_1^a \lambda_2^a)\, a\, r_{12}$$

string tension $\sigma = (16/3)\, a \sim 1$ GeV/fm

- **Color magnetic interaction <= one gluon exchange**

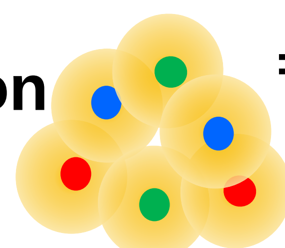
$$\mathcal{H}_{cs} = -\frac{f_{cs}}{m_i m_j}(\lambda_i^c \cdot \lambda_j^c)(\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j)$$



quark mass dependence $m_u/m_s \sim 3/5$

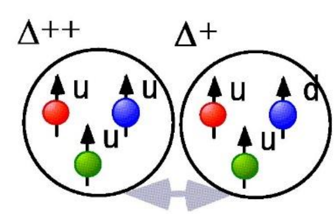
Origin of N-Δ (octet-decuplet), Λ-Σ mass difference

- **GRM (共鳴群法）calculation for colorless $(0s)^6$ state**



=> quark Pauli effect

e.g. ΔΔ (S=3, I=2) *forbidden*



Predictions from Quark Cluster Model

- **H dibaryon （no quark Pauli, attractive color magnetic interaction）**

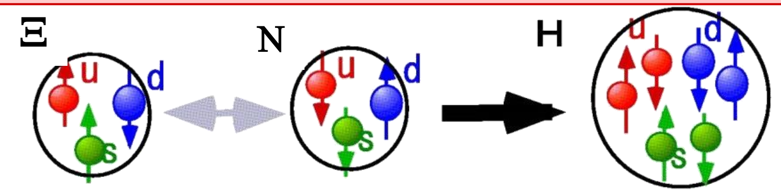
  H dibaryon（6 quark state) exists. (Jaffe's prediction)

  H: **[uuddss]$_{S=0}$ SU$_f$(3) X SU$_f$(3) flavor singlet state has "attractive core"**

  $$BB^{(1)} = -\sqrt{\frac{1}{8}}\Lambda\Lambda + \sqrt{\frac{3}{8}}\Sigma\Sigma \ldots \sqrt{8}$$

  H lighter than ΛΛ does not exist.
  Lattice suggests it between ΛΛ and ΞN mass?

  Ξ–N (S=0,I=0) is strongly attractive.



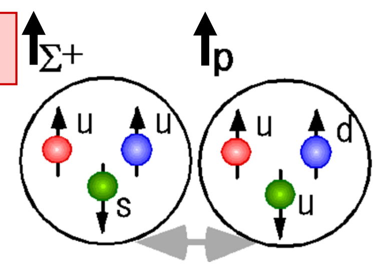
- **ΣN (S=1,T=3/2) strong repulsion （quark Pauli effect)**

  Suggested（ΣN spin/isospin averaged force is strongly repulsive）

- **LS力($L_{YN}S_Y$) Λ–N: almost zero** ***Confirmed from hypernuclei***

  Σ–N: as large as N-N

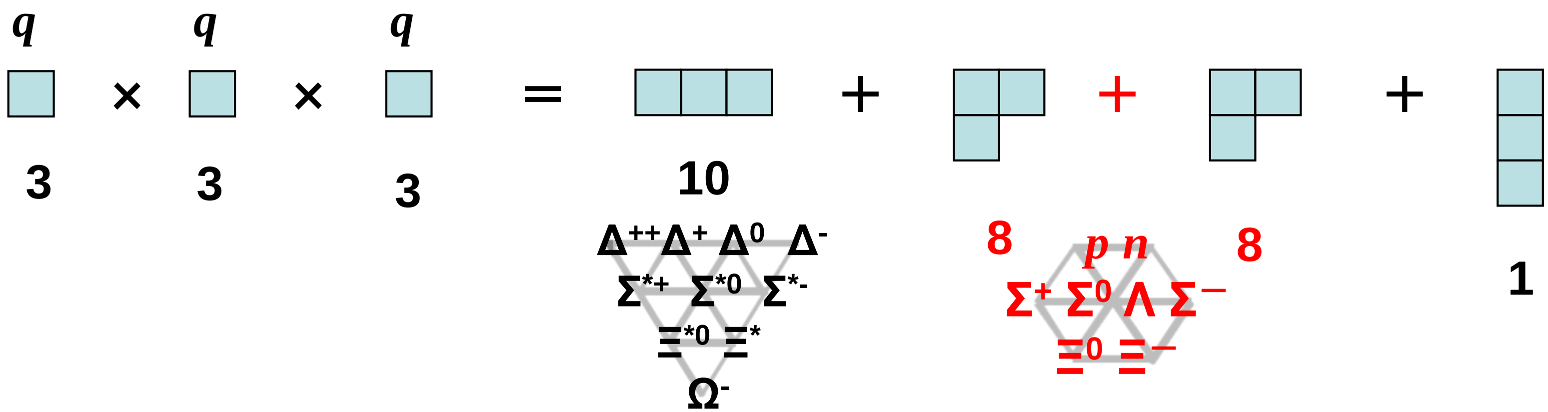
  Suggested in scattering exp.

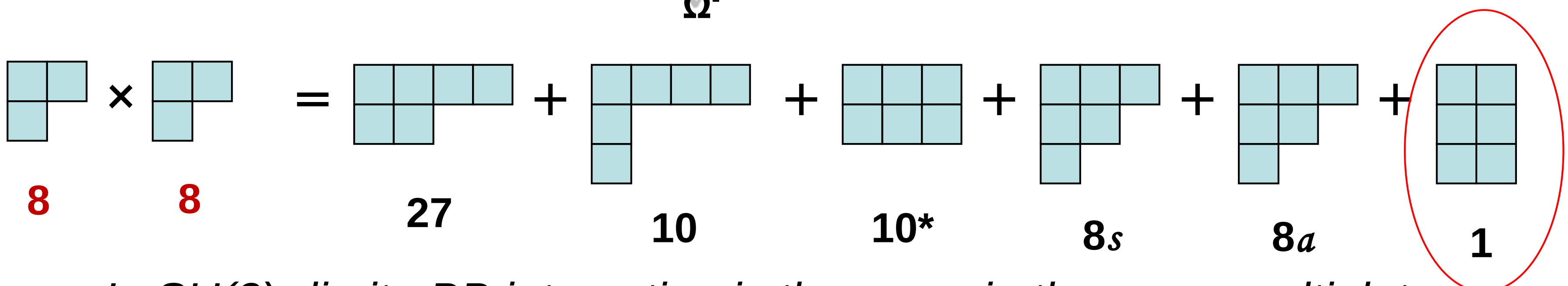


Lattice QCD calc. produces these characteristics.

Extension from nuclear force (u,d) to BB forces (u,d,s) help us understand the origin of the short-range part of nuclear force

"Baryon" and "Baryon-Baryon" in flavor SU(3) symmetry





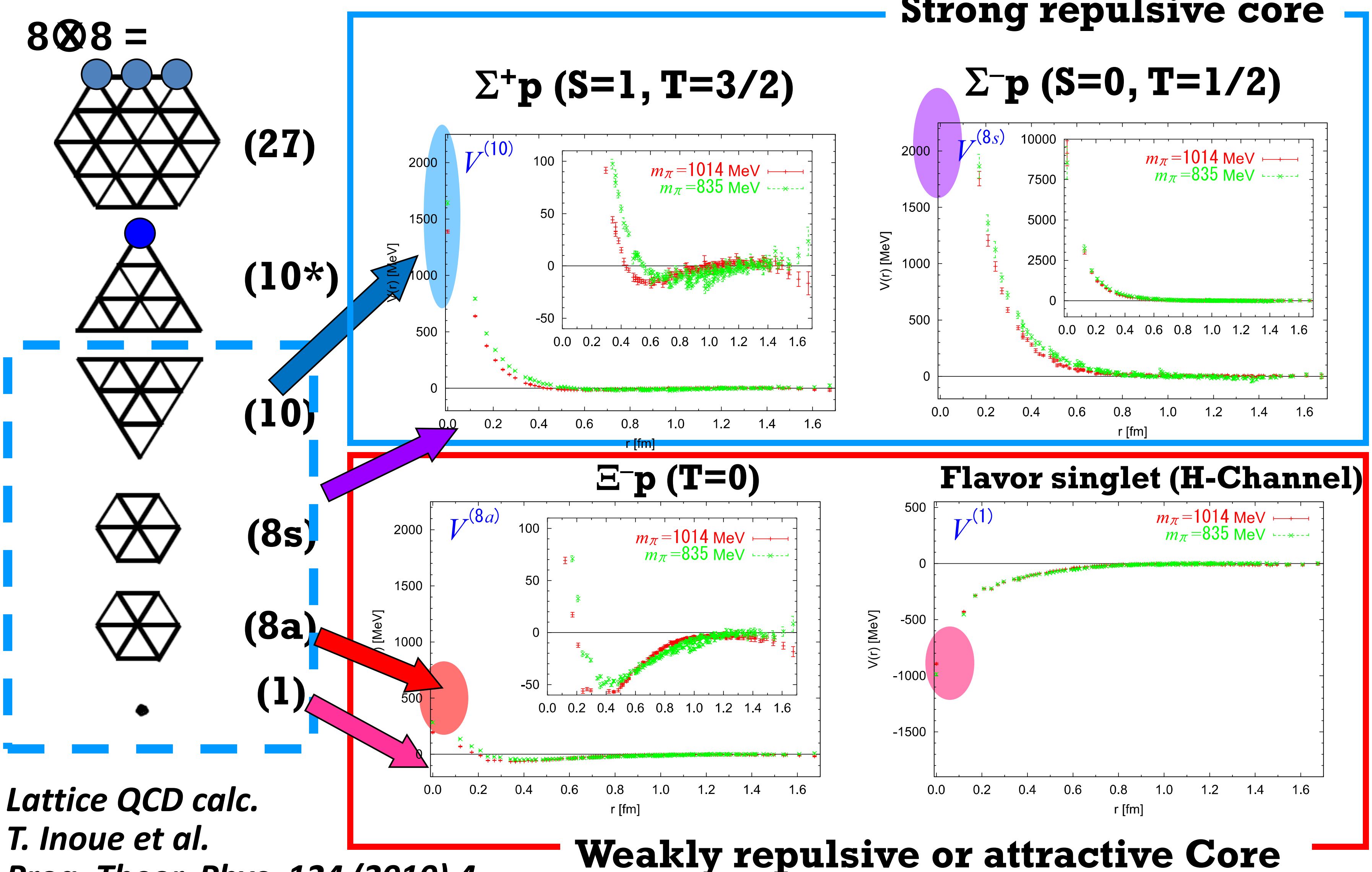
In $SU(3)_f$ limit, BB interaction is the same in the same multiplet

	Flavor symmetric states			Flavor anti-symmetric states		
	27	8	1	$\underline{10}$	10	8
Pauli	mixed	forbidden	allowed	mixed	forbidden	mixed
CMI	repulsive	repulsive	attractive	repulsive	repulsive	repulsive

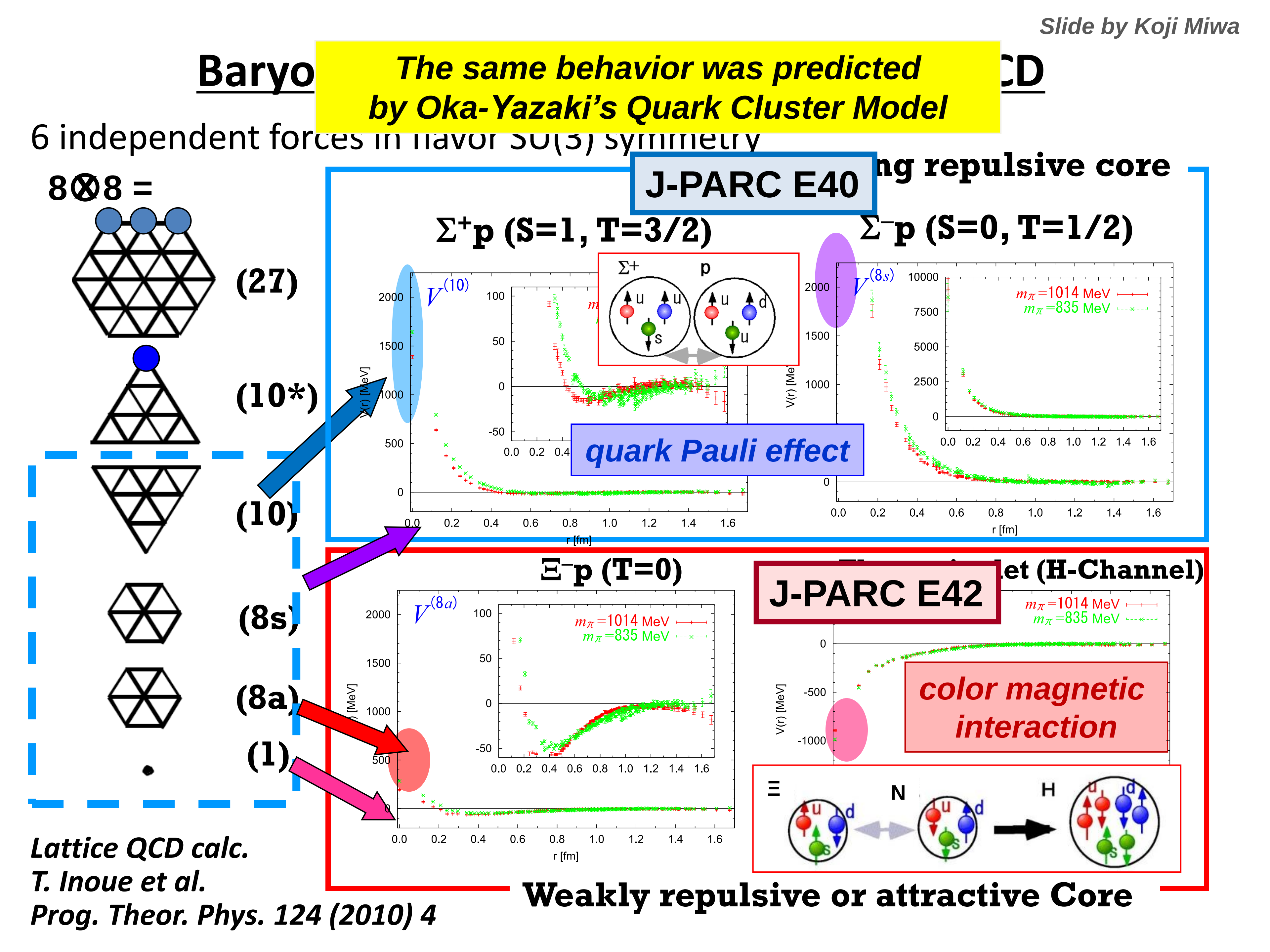
Slide by Koji Miwa

Baryon Baryon interaction by Lattice QCD

6 independent forces in flavor SU(3) symmetry



Lattice QCD calc.
T. Inoue et al.
Prog. Theor. Phys. 124 (2010) 4

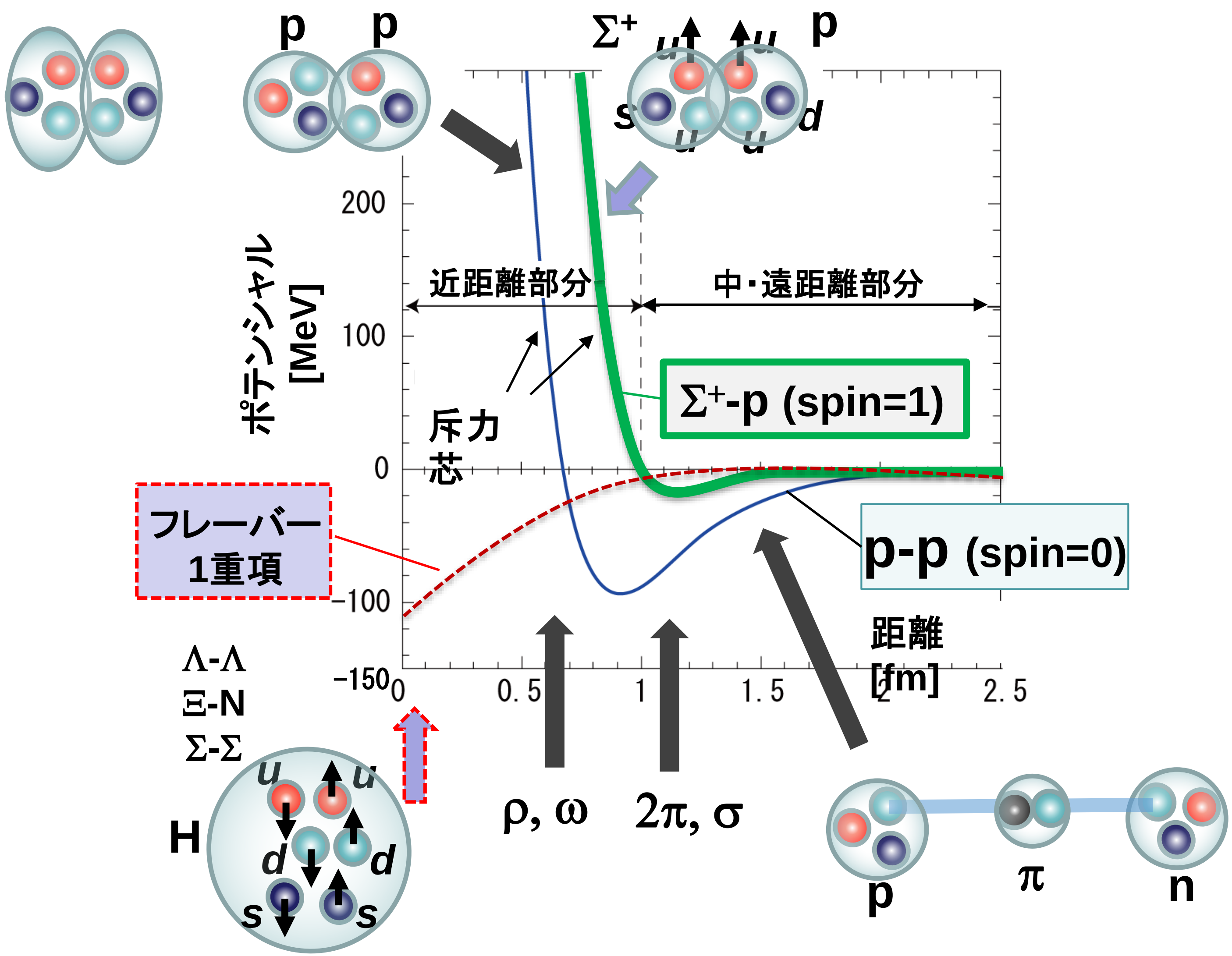

Slide by Koji Miwa
Baryo... CD
The same behavior was predicted
by Oka-Yazaki's Quark Cluster Model
6 independent forces in flavor SU(3) symmetry
8⊗8 =
(27)
(10*)
(10)
(8s)
(8a)
(1)
J-PARC E40
...ng repulsive core
Σ+p (S=1, T=3/2)
Σ−p (S=0, T=1/2)
quark Pauli effect
Ξ−p (T=0)
J-PARC E42
...et (H-Channel)
color magnetic interaction
Weakly repulsive or attractive Core
Lattice QCD calc.
T. Inoue et al.
Prog. Theor. Phys. 124 (2010) 4

ストレンジネスを含むバリオン間力の研究

Studies of baryon-baryon interactions with strangeness

H dibaryon

バリオン間相互作用（B01班の研究対象）

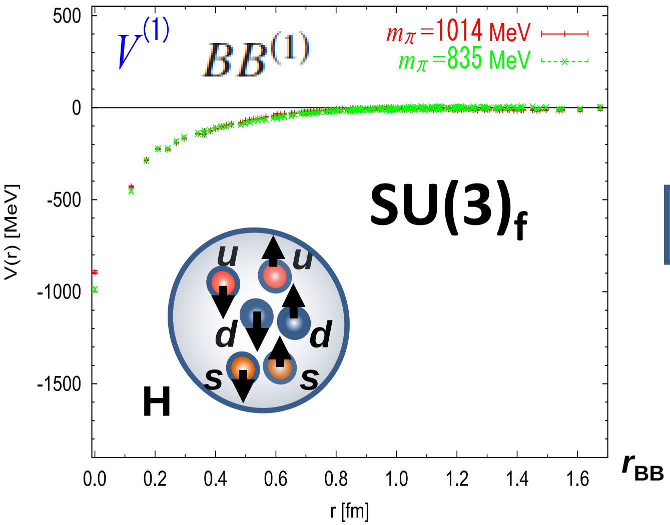


Lattice Prediction for H

HAL collaboration: Inoue, Sasaki, et al.

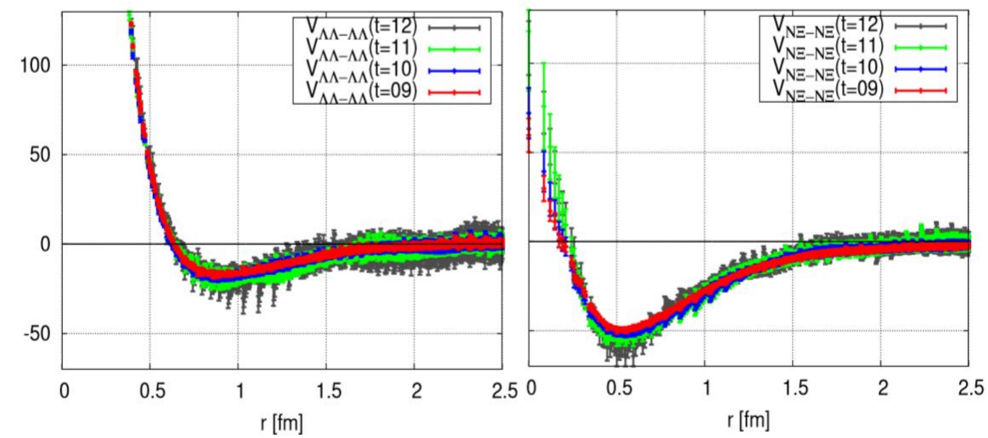
$$BB^{(1)} = -\sqrt{\frac{1}{8}}\Lambda\Lambda + \sqrt{\frac{3}{8}}\Sigma\Sigma + \sqrt{\frac{4}{8}}N\Xi,$$

$m_u = m_d = m_s$ (heavy)

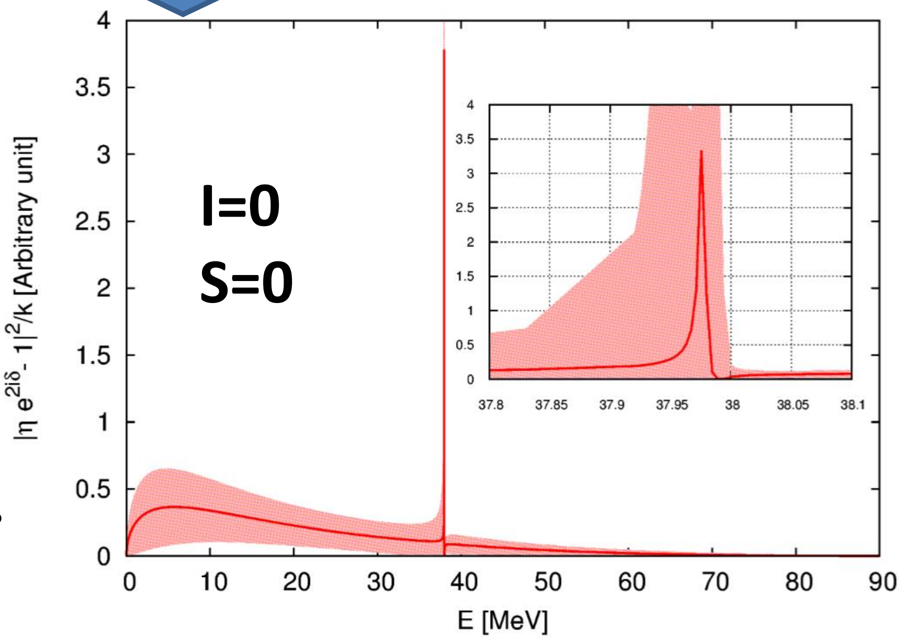


Attractive core
-> B in BB$^{(1)}$ is not a stable cluster

Realistic masses *Sasaki et al.(2018)*



(a) $V_{\Lambda\Lambda-\Lambda\Lambda}$ (b) $V_{N\Xi-N\Xi}$



In reality, mixture of a 6 quark state and a two-hadron (~ΞN) molecule?

H dibaryon search at J-PARC (E42)

Experiments:

$\Lambda\Lambda$ **hypernclei => $m_H > m_{\Lambda\Lambda}$**

Lattice :

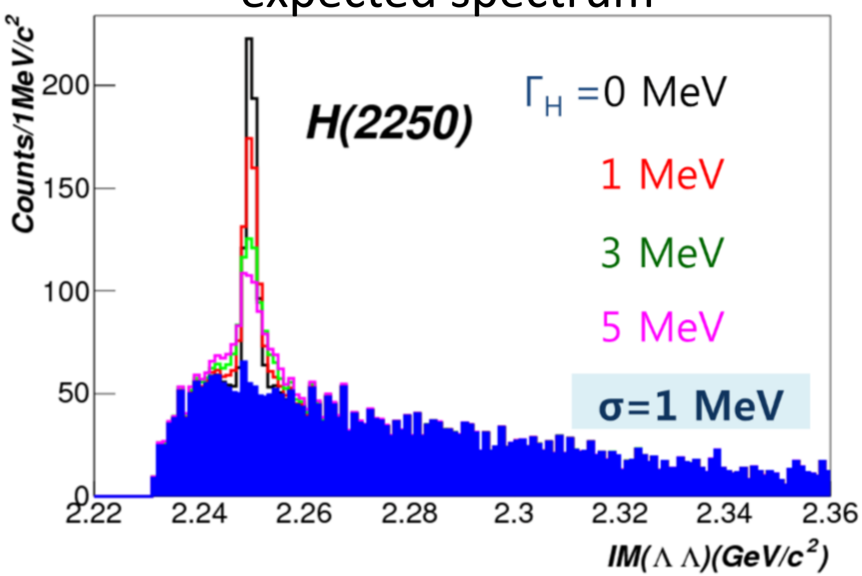
$m_{\Xi^- p} > m_H > m_{\Lambda\Lambda}$

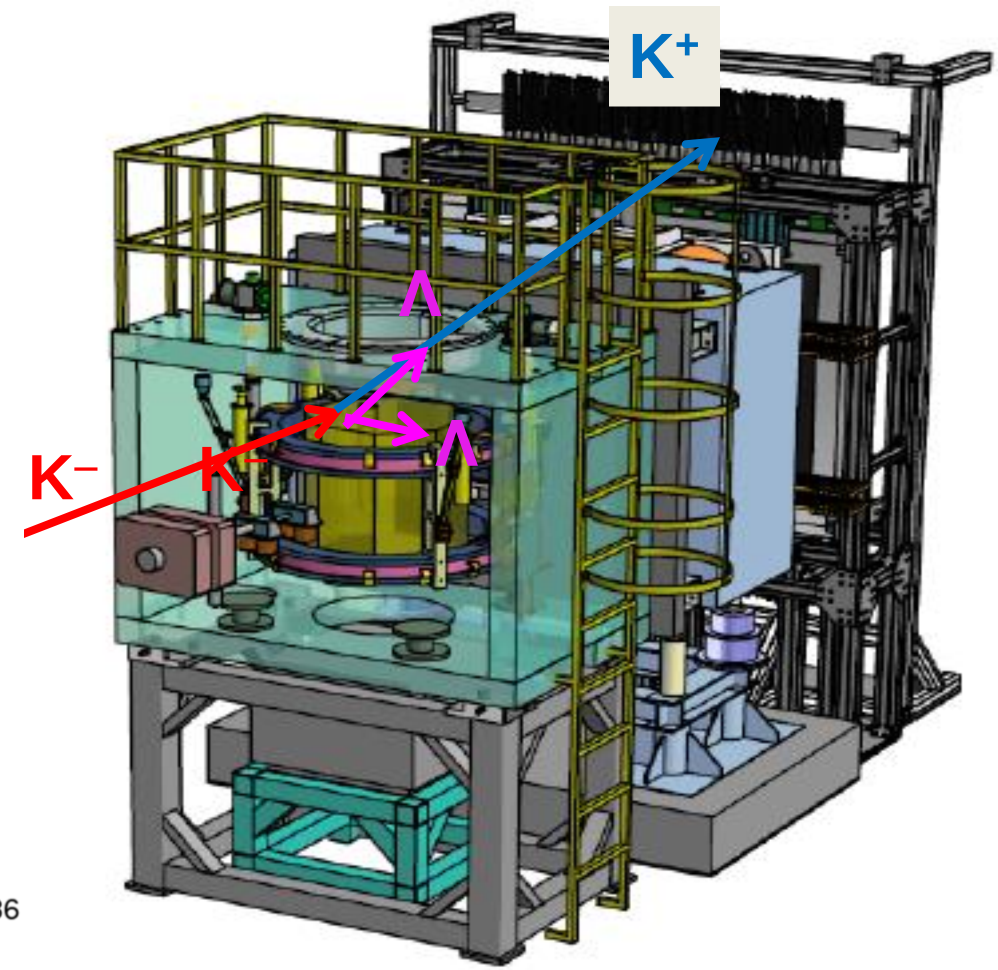
Hyperon spectrometer ready
SC Helmholtz magnet + TPC

$K^- \, {}^{12}C \Rightarrow H + X + K^+$

$H \Rightarrow \Lambda\Lambda$

expected spectrum



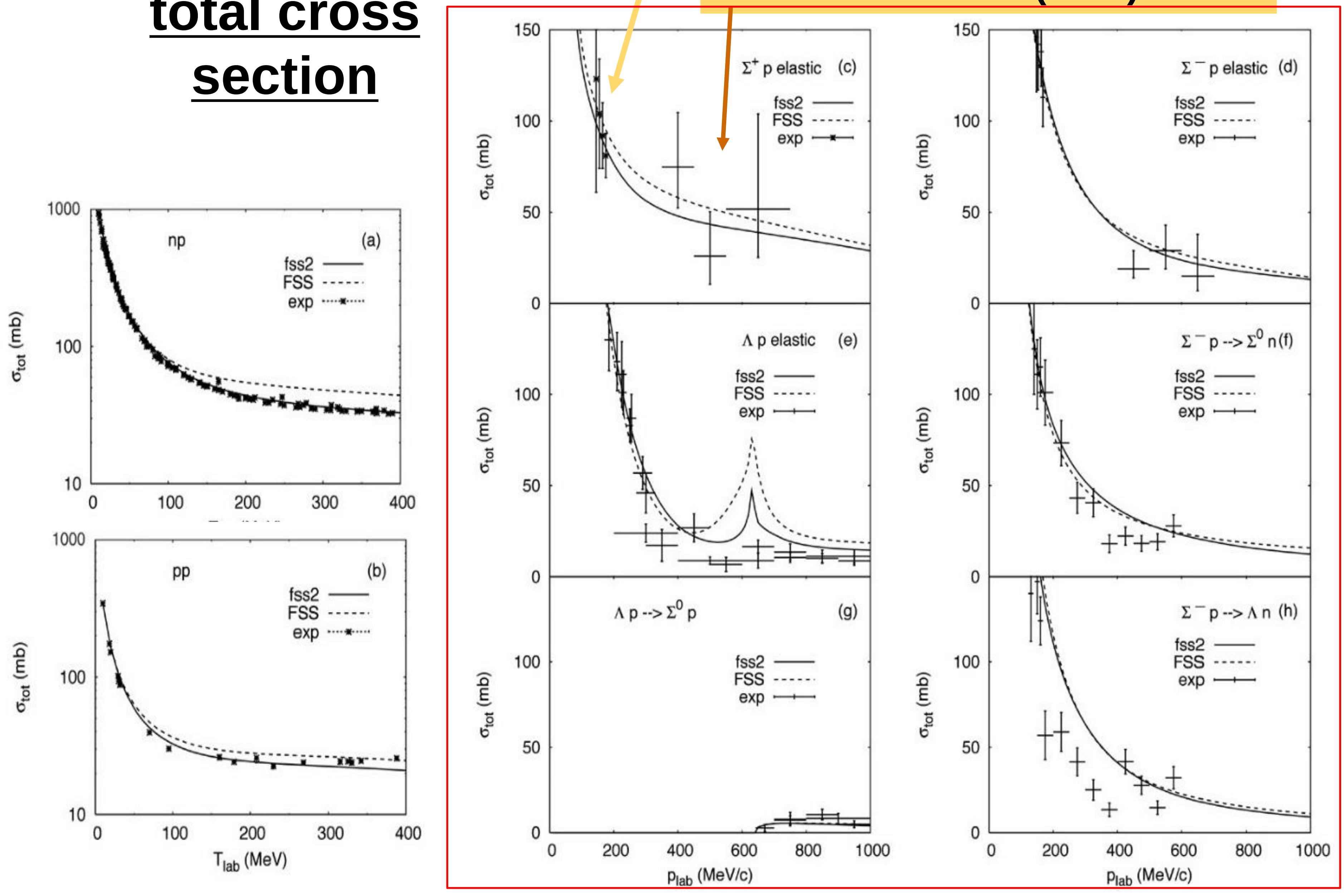


Scattering experiments

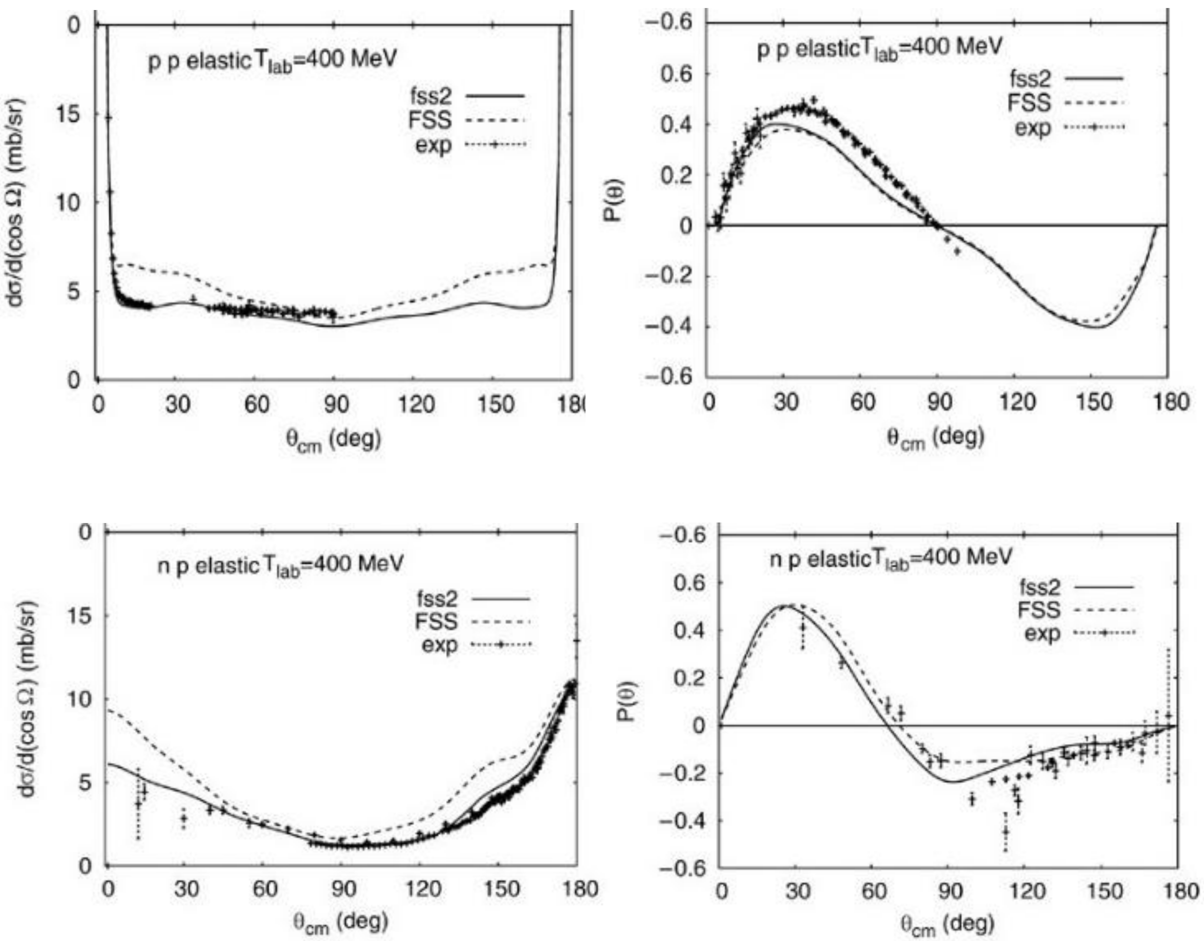
NN, YN scattering data total cross section

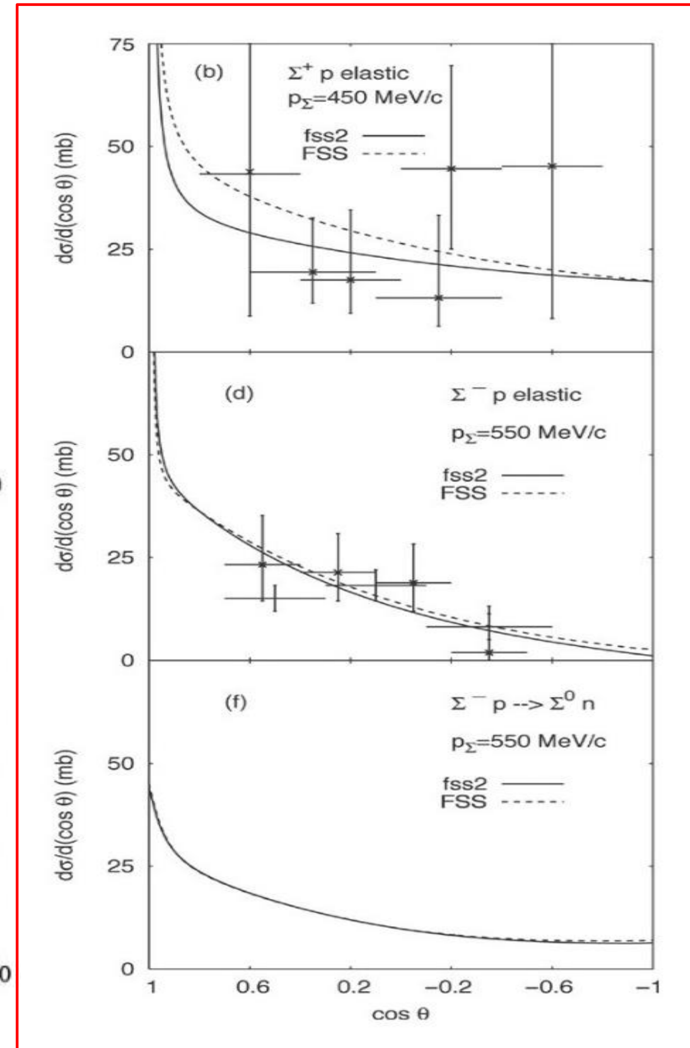
Bubble chamber (CERN) in 1960s~70s

Scintillation fiber (KEK) in 90s



Differential cross section, polarization





微分断面積と散乱振幅

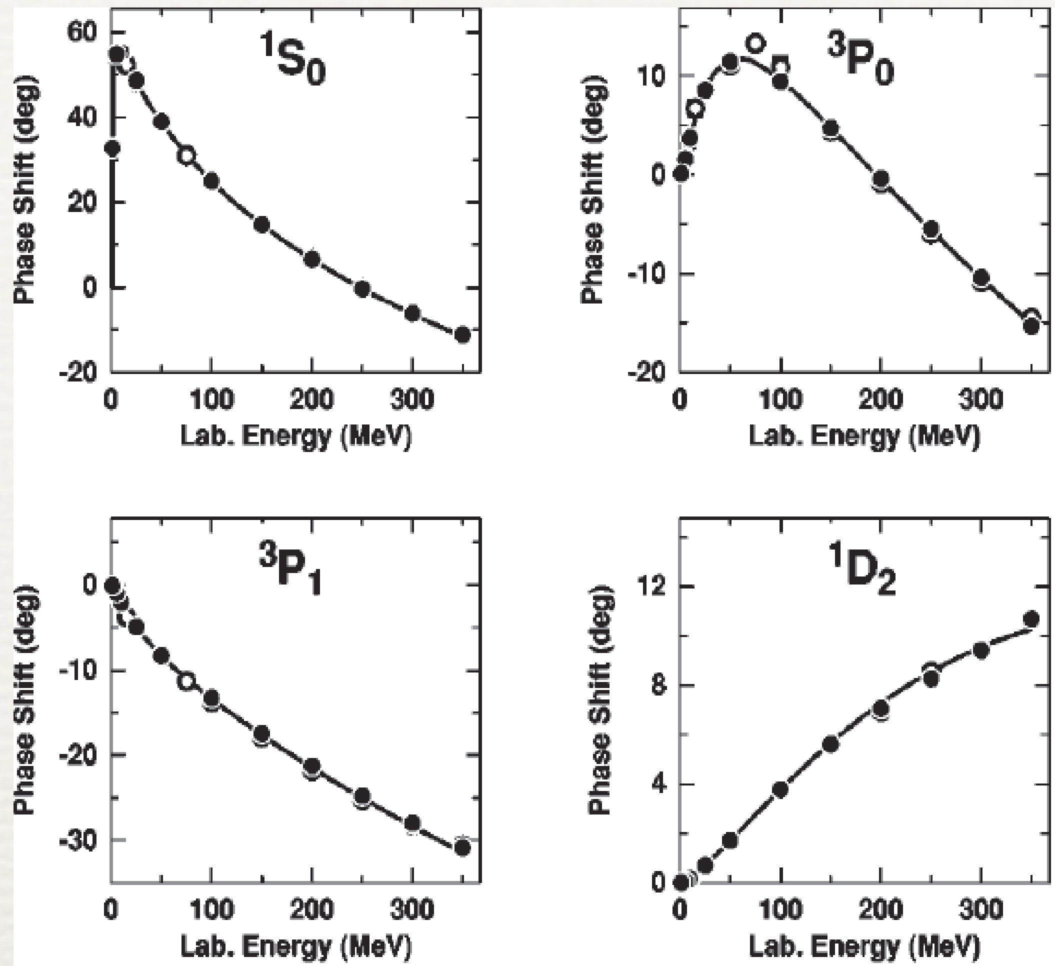
$$\frac{d\sigma}{d\Omega} = |f(\theta)|^2$$

散乱振幅の部分波分解

$$f(\theta) = \frac{1}{k}\sum_{l=0}^{\infty}(2l+1)\,e^{i\delta_l}\sin(\delta_l)P_l(\cos\theta)$$

Phase shift

R. MACHLEIDT

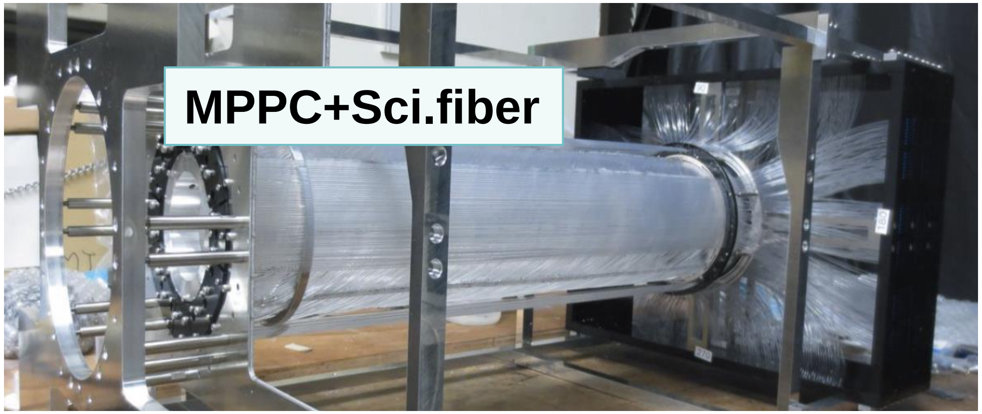


Scattering data
(angular distribution)
-> phase shift δ_l for each l

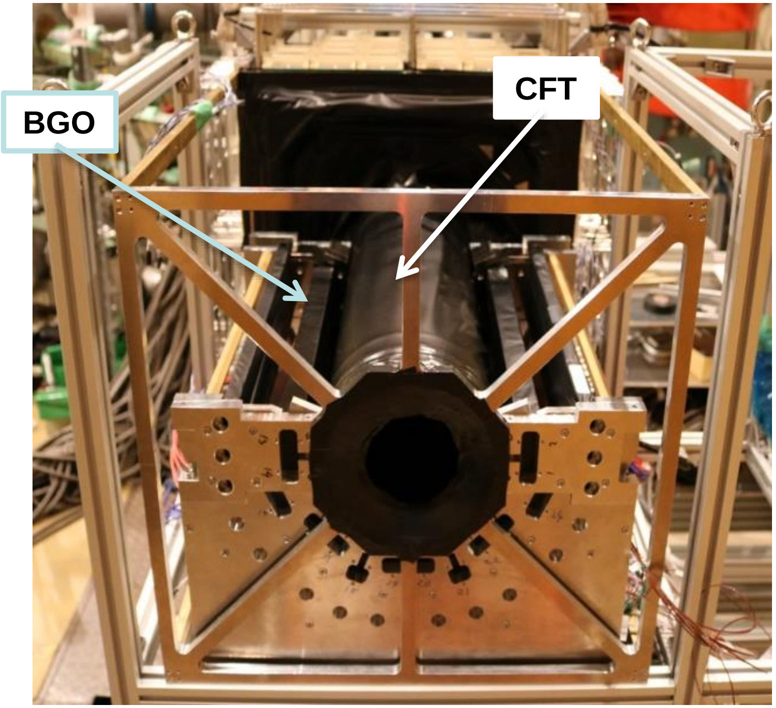
No phase shift data
for YN interactions

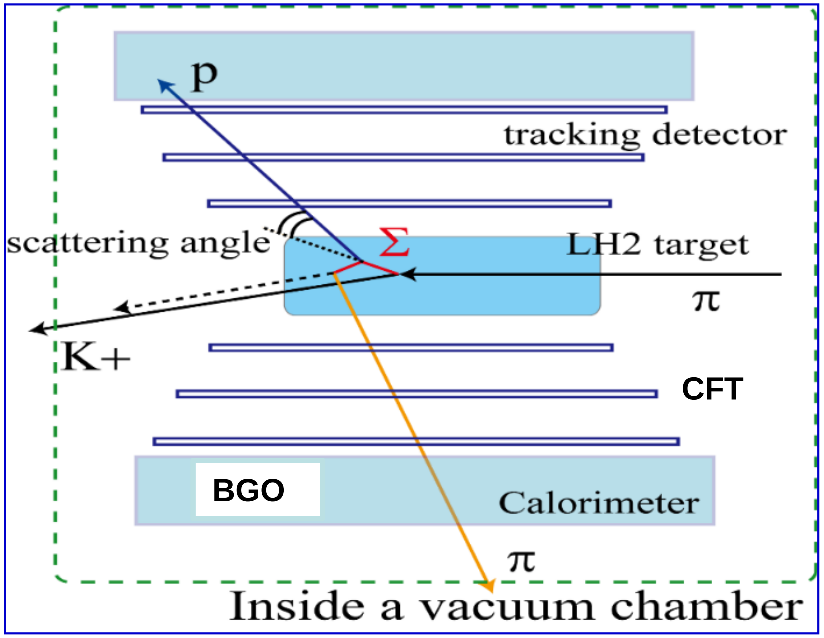
New type of $\Sigma^{\pm}p$ Scattering Experiment at J-PARC

(E40, Miwa et al.)



- 1.3 GeV/c π^{+-} p -> $K^{+}\Sigma^{+-}$ reaction
- Σ^{+-} momentum from (π^{+-},K^{+})
- Measure p momentum vector -> Σp scattering events identified kinematically



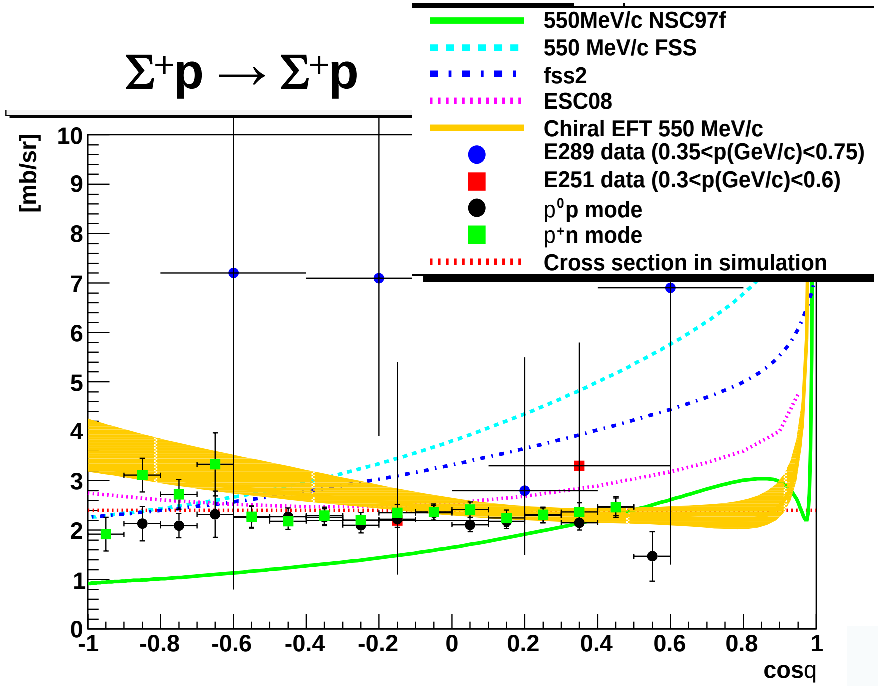


⇒ **dσ/dΩ for $\Sigma^{+}p$, $\Sigma^{-}p$, $\Sigma^{-}p \to \Lambda n$ (p_{Σ} = 400-700 MeV/c)**

=> confirm quark Paul effect

Slide by K. Miwa

Expected accuracy



ds/dΩ : 2.4mb/sr isotropic (assumed)

- 20,000 scattering events
- derive dσ/dΩ for 3 momentum ranges

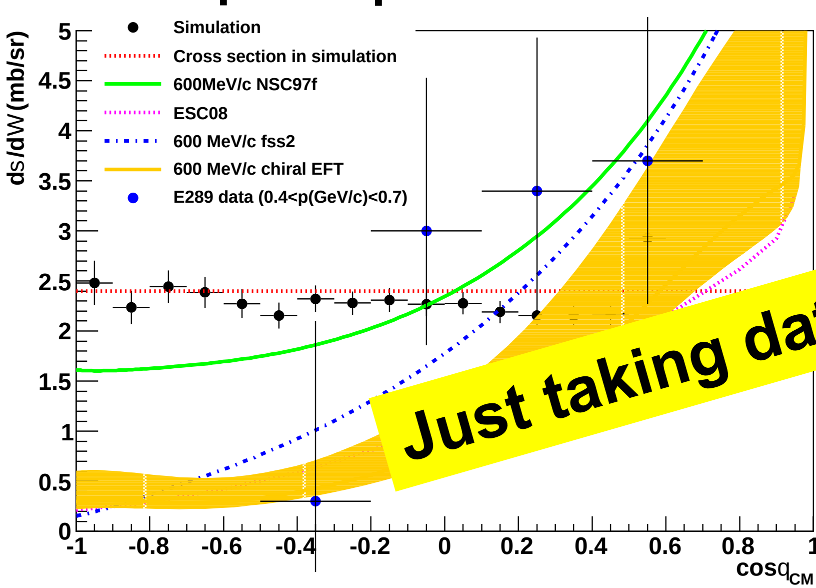
☐ $\Sigma^- p$: ±0.11 (stat.) ±0.15 (syst.) mb/sr

☐ $\Sigma^+ p$: ±0.15 (stat.) ±0.15 (syst.) mb/sr

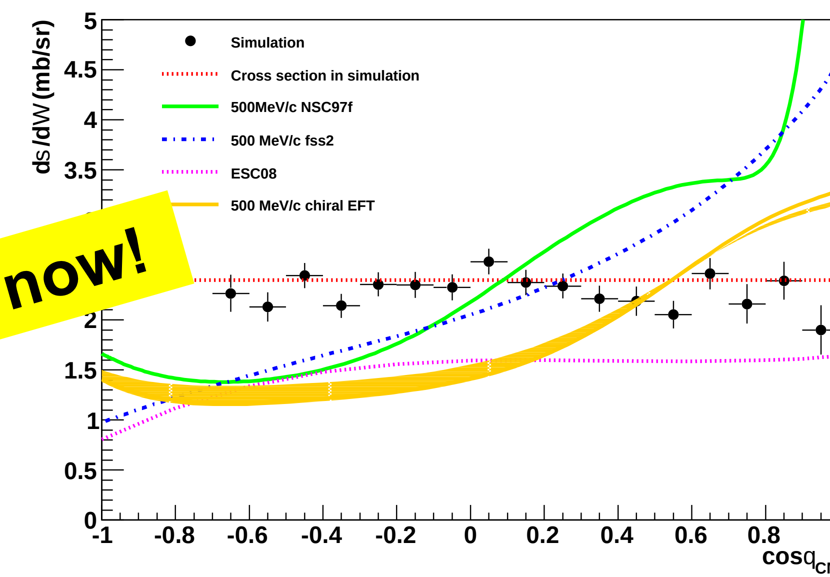
Simulation for p_Σ = 0.5 – 0.6 (GeV/c)

/sr

$\Sigma^- p \rightarrow \Sigma^- p$



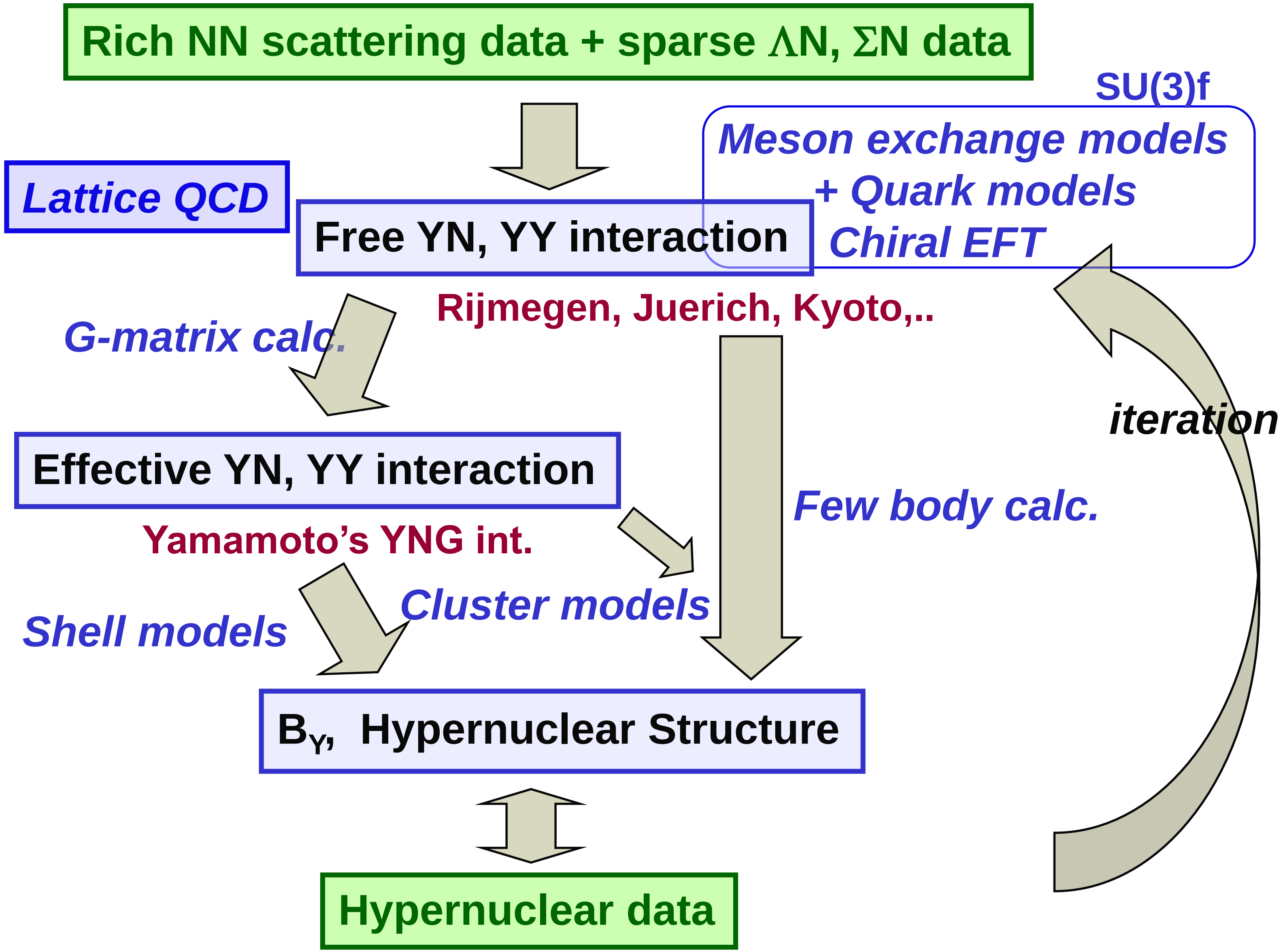
$\Sigma^- p \rightarrow \Lambda n$



Just taking data now!

Studies of YN, YY interactions from hypernuclei

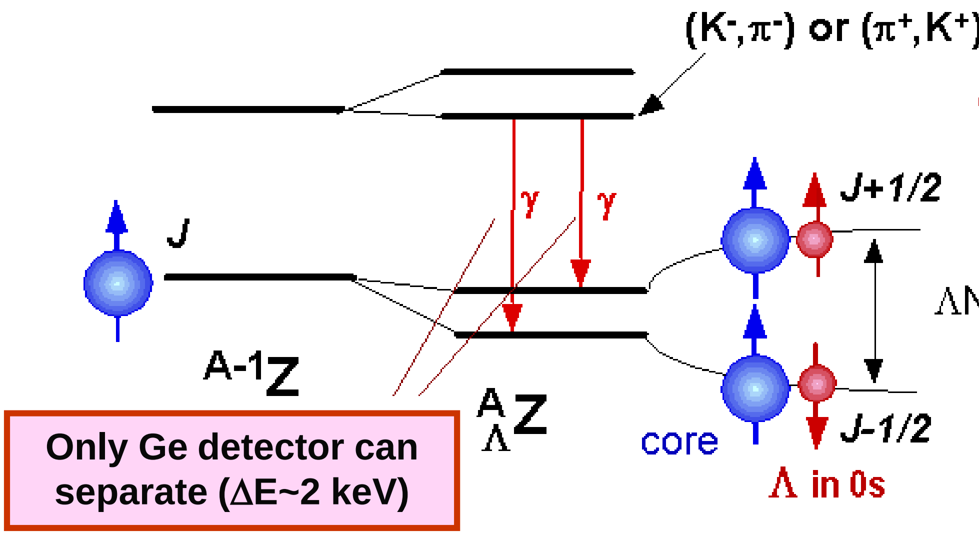
How to construct YN, YY interactions using nuclear data?



ΛN spin-dependent interactions and hypernuclear levels

スピン依存相互作用とハイパー核レベル

■ Low-lying levels of Λ hypernuclei



"Hypernuclear Fine Structure"

split by
ΛN spin-dependent
interactions
$\lesssim$ 0.1 MeV

Level spacing: Linear combination of *Δ*, *S_Λ*, *S_N*, *T*

■ Two-body ΛN effective interaction

Dalitz and Gal, Ann. Phys. 116 (1978) 167
Millener et al., Phys. Rev. C31 (1985) 499

$$V_{\Lambda N}^{eff} = V_0(r) + V_\sigma(r)\, \vec{s}_\Lambda \vec{s}_N + V_\Lambda(r)\, \vec{l}_{\Lambda N}\vec{s}_\Lambda + V_N(r)\, \vec{l}_{\Lambda N}\vec{s}_N + V_T(r)\, S_{12}$$

$\bar{V}$ — Δ — S_Λ — S_N — T

"interaction strengths"

Well know from U_Λ = - 30 MeV

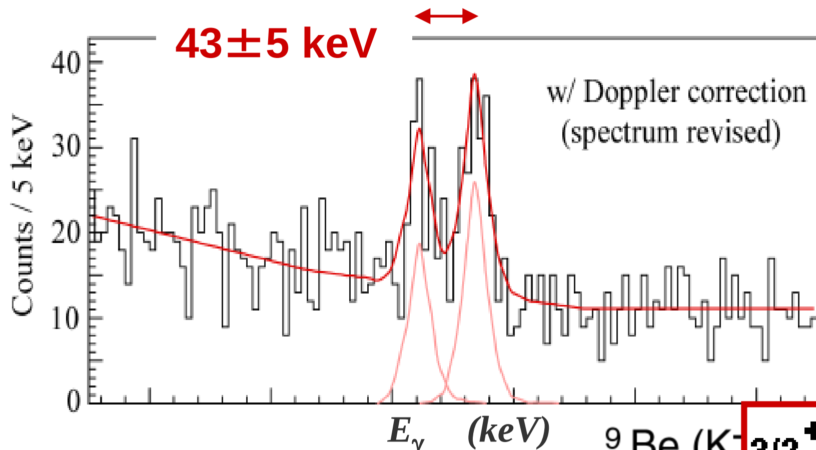
p-shell: 5 radial integrals for $s_\Lambda p_N$ w.f.

$$\Delta = \int V_\sigma(r)\, |u_{p_N}(r)|^2 r^2 dr, \quad r = r_{p_N} - r_{s_\Lambda}$$

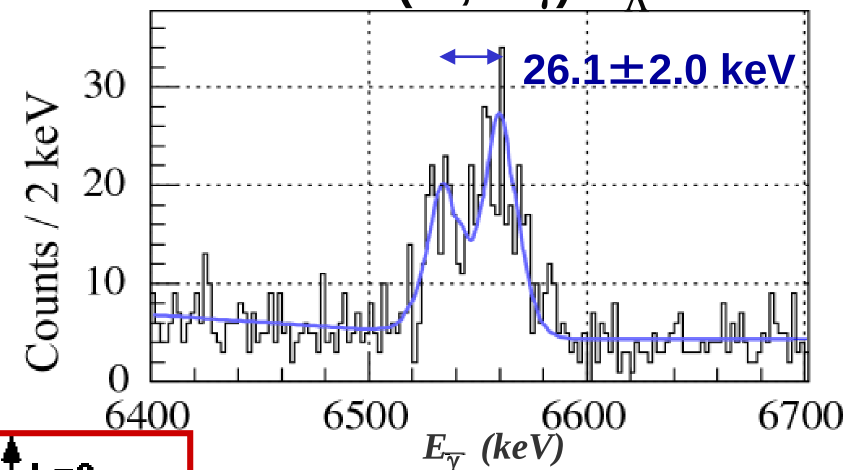
Observation of "Hypernuclear Fine Structure"

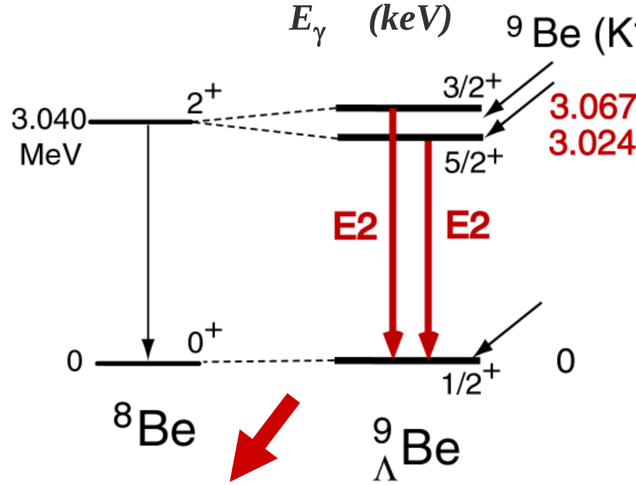
BNL E930 (AGS D6 line + Hyperball)

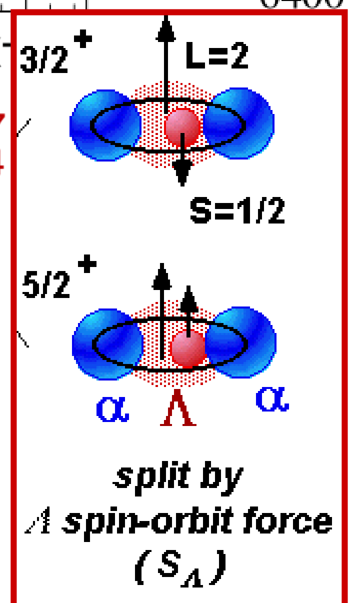
^{9}Be (K$^-$, π^- γ) $^{9}_{\Lambda}$Be

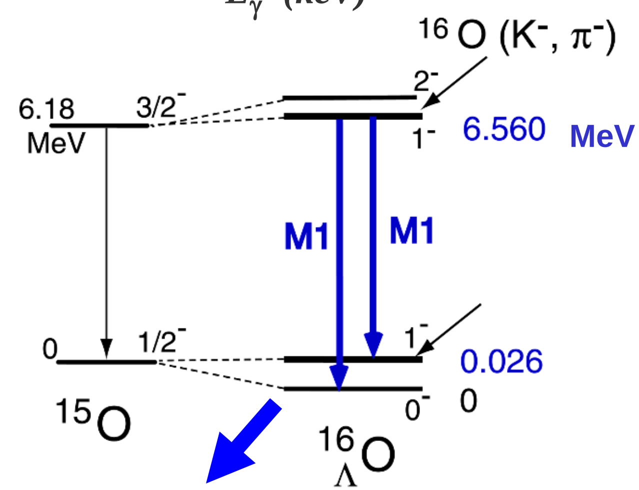


^{16}O (K$^-$, π^- γ) $^{16}_{\Lambda}$O









S_Λ = -0.01 MeV

PRL 88 (2002) 082501

consistent with Quark Cluster Model

T = 0.03 MeV

PRL 93 (2004) 232501

consistent with Meson Exch. Model

ΛN spin-dependent interactions (D.J. Millener)

ΛN spin-dependent interaction strengths determined:

Δ = 0.33 (A>10), 0.42 (A<10), S_Λ = -0.01, S_N = -0.4, T =0.03 MeV

"Much smaller spin-dependent forces than NN"

- **Almost all p-shell levels are reproduced within a few 10 keV by these parameters.**
- **Test BB interaction models to improve them:**

		Δ	S_Λ	S_N	T (MeV)
Nijmegen meson-exchange models	ND	-0.048	-0.131	-0.264	0.018
	NF	0.072	-0.175	-0.266	0.033
	NSC89	1.052	-0.173	-0.292	0.036
	NSC97f	0.421	-0.149	-0.238	0.055
	ESC04a	0.381	-0.108	-0.236	0.013
	ESC08a	0.146	-0.074	-0.241	0.055
	("Quark model"		0.0	-0.4)	
	Exp.	0.3	-0.01	-0.4	0.03

LS force:

All Nijmegen models fail.

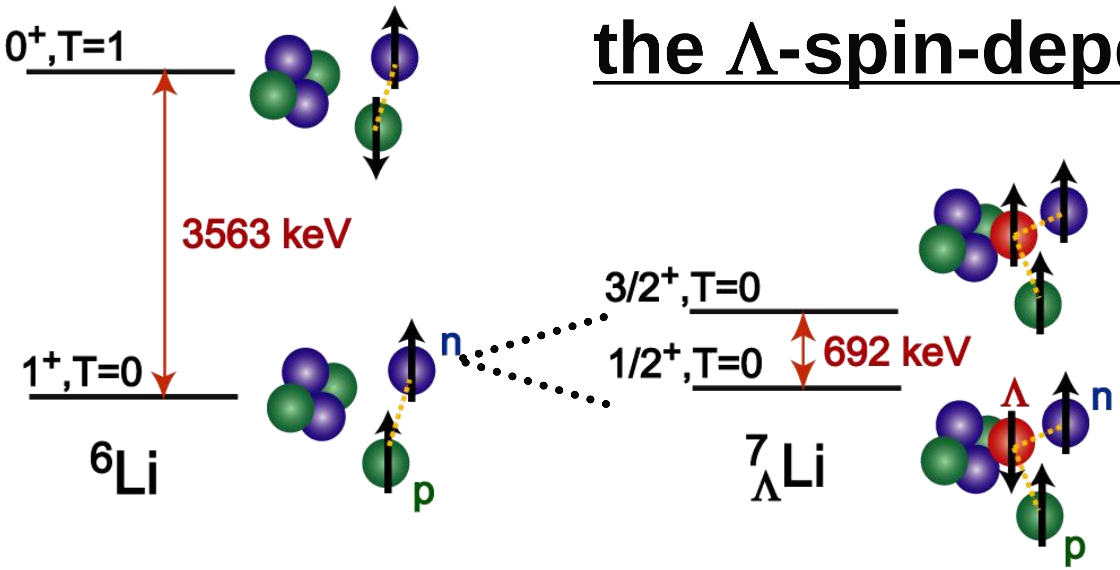
Quark model looks OK.

ΛN-ΣN force is not well studied yet. => s-shell hypernuclei

ΛN interaction in nuclear matter? => heavier hypernuclei

How weak are the Λ-spin-dependent forces?

spin-spin force

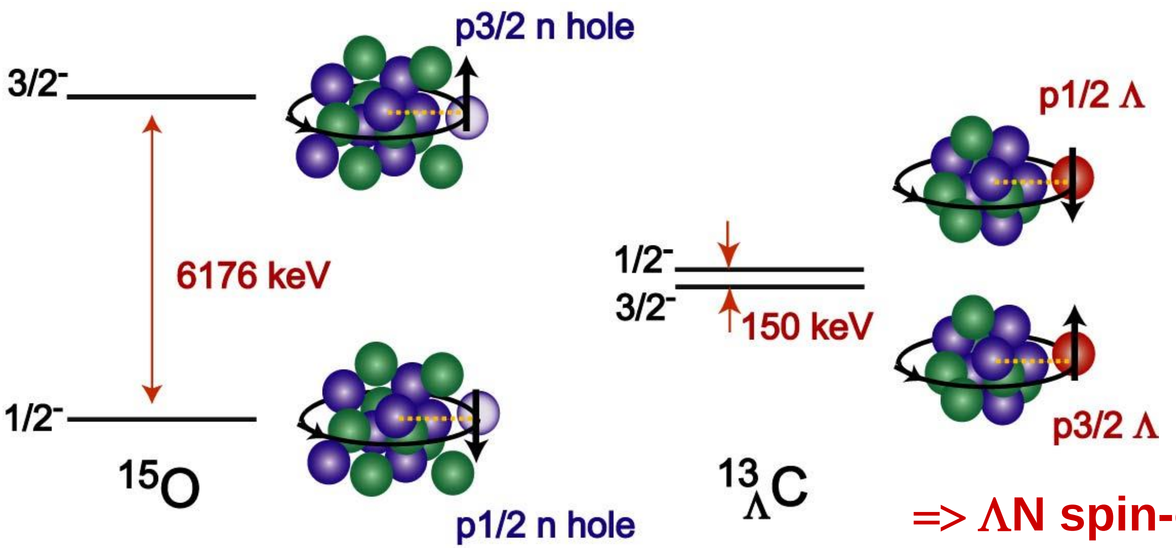


Tamura et al., PRL 84 (2000) 5963

$\Delta = 0.42$ MeV

=> ΛN spin-spin force
~ 1/10 of NN spin-isospin force

spin-orbit force



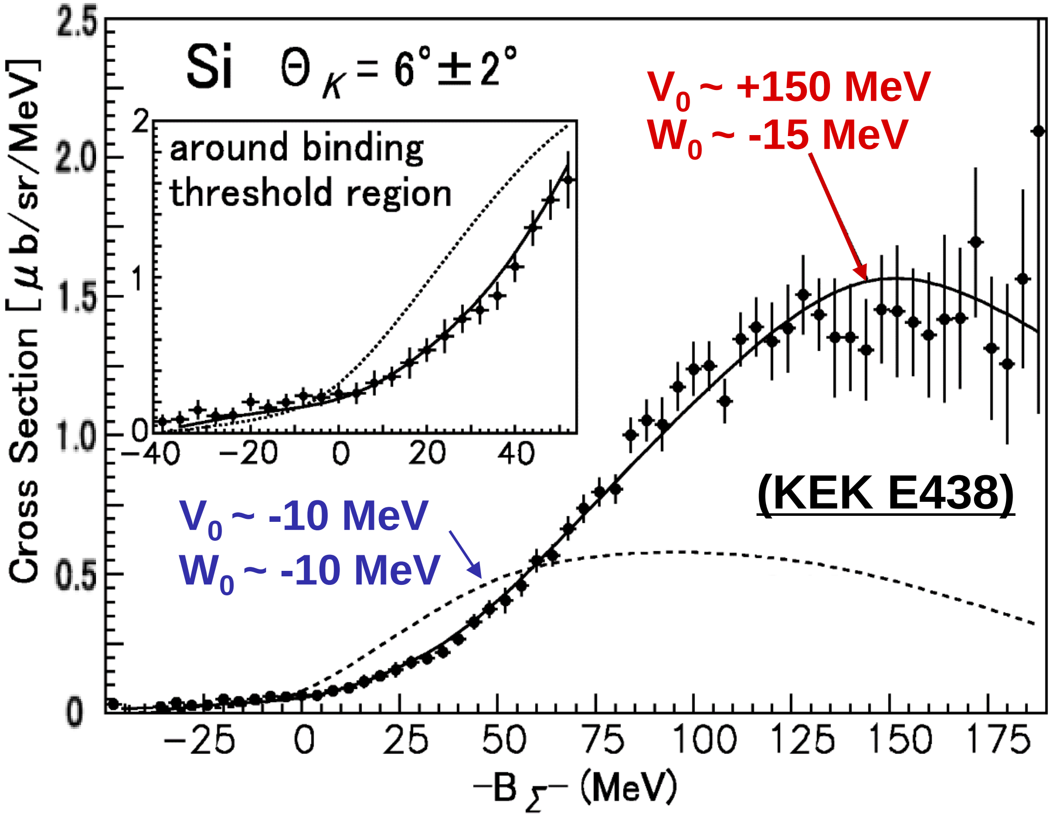
Ajimura et al., PRL 86 (2001) 4255

$(S_\Lambda = -0.01$ MeV$)$

=> ΛN spin-orbit force
~ 1/40 of NN spin-orbit force

Σ^--^{28}Si potential – repulsive ΣN force

^{28}Si (π^-,K^+) at 1.2GeV/ with SKS



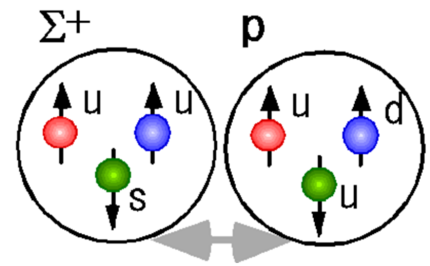
Noumi et al., PRL 87(2002) 072301

$$U_\Sigma = (V_0 + i\,W_0)\,f_{WS}(r)$$

Suggestign a strongly repulsive potential

(V_Σ~ +30 MeV)

- **This strong repulsion is nuclear matter is due to strong repulsion predicted by Quark Cluster Model and Lattice QCD ?**



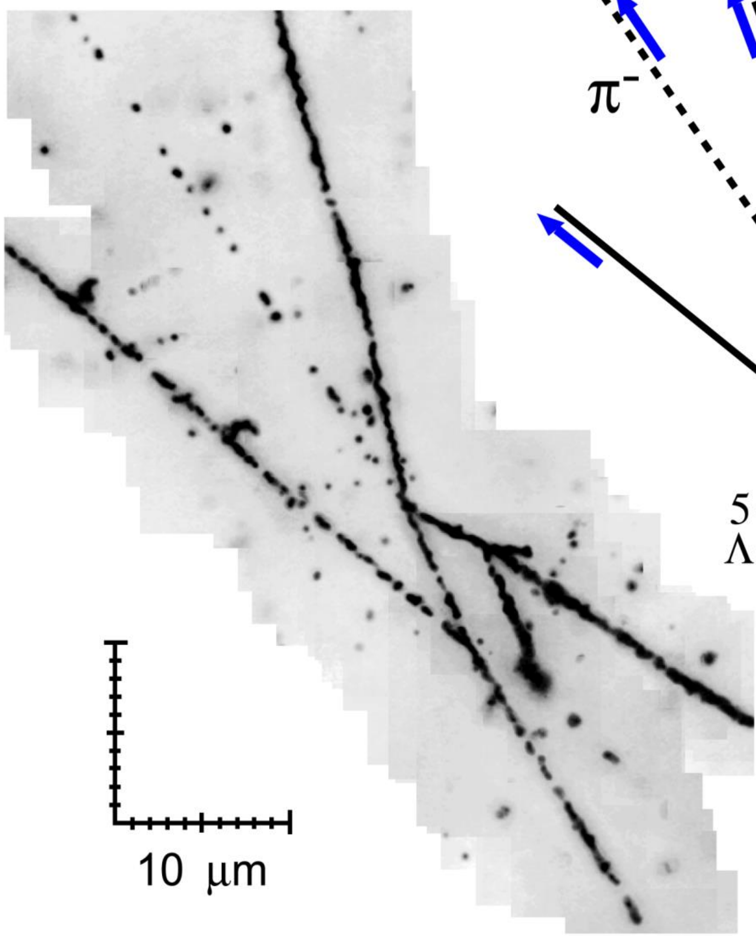
ΣN (I,S) = (3/2,1)

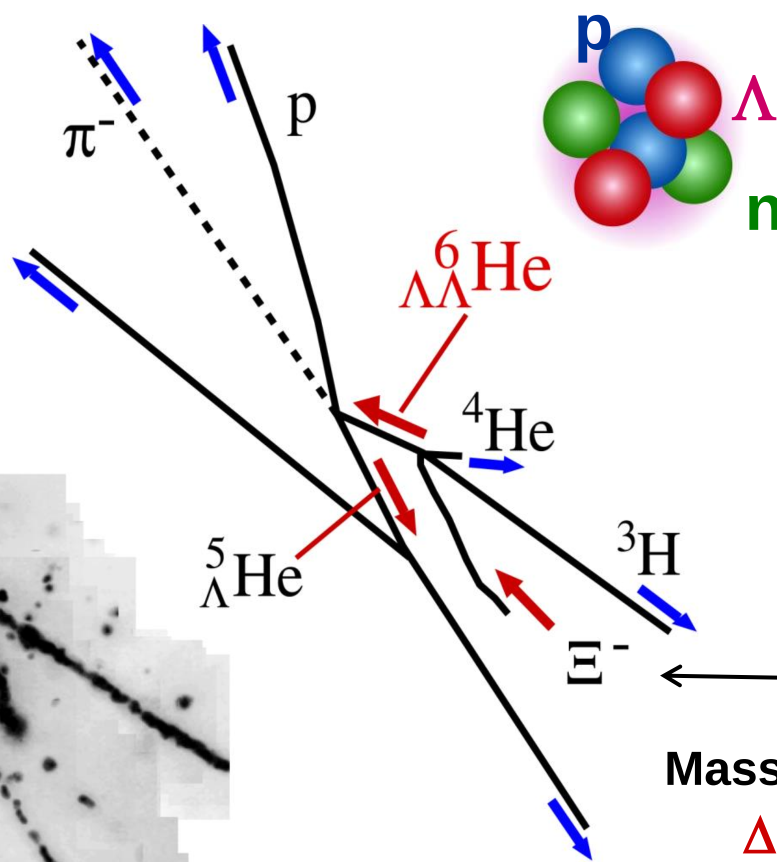
(3/2,1) : (1/2,1) : (3/2,0) : (1/2,0)
= 12 : 6 :4 : 1
for Σ in nuclear matter

- **No Σ in neutron stars due to strong repulsion in Σ^- n ?**

ΛΛ interaction from ΛΛ hypernuclei

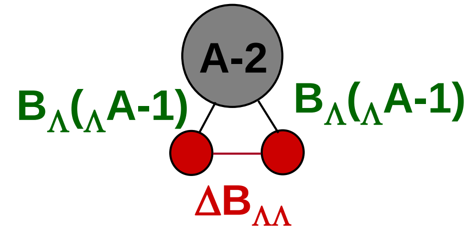
Nagara event





Takahashi et al., PRL 87 (2001) 212502

"Triple magic" nucleus



$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2B_{\Lambda}({}_{\Lambda}A\text{-}1)$,

$B_{\Lambda\Lambda} = M(A\text{-}2) + 2\,M(\Lambda) - M({}_{\Lambda\Lambda}A)$

← $K^{-}\,p \rightarrow \Xi\,K^{+}$ reation

Mass of $^{6}_{\Lambda\Lambda}He$ ->

$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV

- ΛΛ 間相互作用は、弱い引力
- 束縛した H dibaryon は存在しない
  （核内で ΛΛ→H が起こるはず）

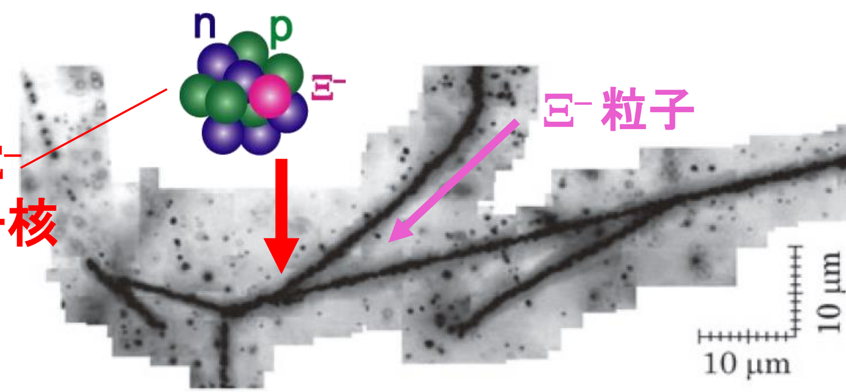
J-PARCで10倍の実験（ ΛΛ核100個）を実施中 (E07,Nakazawa)

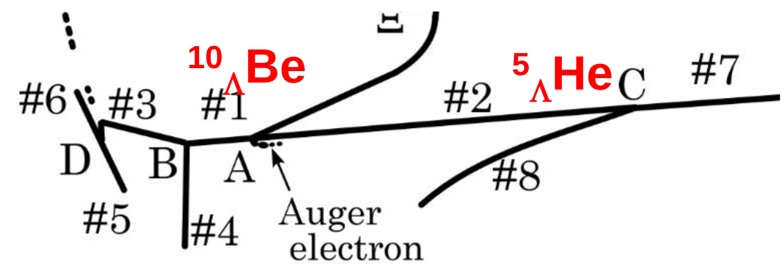
First observation of Ξ hypernucleus

Nakazawa et al., PTEP (2015) 3, 033D02

- J-PARC実験用に開発したエマルジョン全スキャン装置で、過去のKEK-PSの実験で照射したエマルジョンを解析して発見

  $\Xi^- + {}^{14}N \rightarrow {}^{10}_{\Lambda}Be + {}^{5}_{\Lambda}He$ と同定





2015年（平成27年）1月19日（月曜日） 中日

岐大、宇宙創生の謎に一歩

中性子星に「グザイ」存在

岐阜大の仲沢和馬教授（実験物理学）と日本原子力研究開発機構（茨城県）などのグループは、恒星の最終形態である中性子星に含まれていると推定されている素粒子「グザイ」の性質を解明した。中性子星にグザイが存在することをほぼ確定する成果で、宇宙創生の秘密に迫る一歩として注目される。（松野穂波）

結果は、日本物理学会などがインターネットで発表する学術論文誌に近く掲載される。

中性子星は、寿命が尽きた恒星が爆発した後に残る星。大きさは太陽の百万分の一程度だが、質量は約二倍と極めて密度が高い。このため、素粒子のうち陽子や中性子より重い「ラムダ」「シグマ」「グザイ」のいずれかが存在すると考えられた。

仲沢教授は二〇〇一年、通常は陽子と中性子でできている原子核に、ラムダを結合した超原子核を作製。陽子、中性子とラムダが結び付くことが分かり、中性子星に存在する可能性が高まった。シグマは原子核と反発する関係と判明し、残るグザイの性質を解き明かすことが、中性子星を知る最後の鍵と位置付けられていた。グザイは、中性子星より低密度の地球では百億分の一秒で崩壊してしまうため、地球上に存在しないとみられる。このため、仲沢教授らは高エネルギー加速器研究機構（茨城県）で、K中間子という粒子の放射線をダイヤモンドに照射することで、人工的にグザイ粒子を生成。特殊な写真乾板に当てて顕微鏡で撮影した。約八百万枚の画像を分析した結果、窒素の原子核にグザイが吸収された超原子核を発見した。

超原子核内の引力を測定すると、原子核とグザイが互いの電磁力の三十倍の強さで引き合っていた。グザ

仲沢和馬教授

中性子星

大きさは太陽の100万分の1だが重さは2個分

重い素粒子が存在？

太陽　太陽

○=陽子　△=中性子　●=グザイ、ラムダなどの重い素粒子

- Ξ⁻と¹⁴N核の束縛エネルギーを導出

  > 1.11±0.25 MeV　c.f. 0.17 MeV（atomic orbit）

  4.38±0.25MeV if $^{10}_{\Lambda}Be$ is in ground state.

⇒**Ξ⁻N相互作用は引力！**

⇒ **中性子星内部の Ξ⁻ の存在**を強く示唆

BB correlations
---skipped

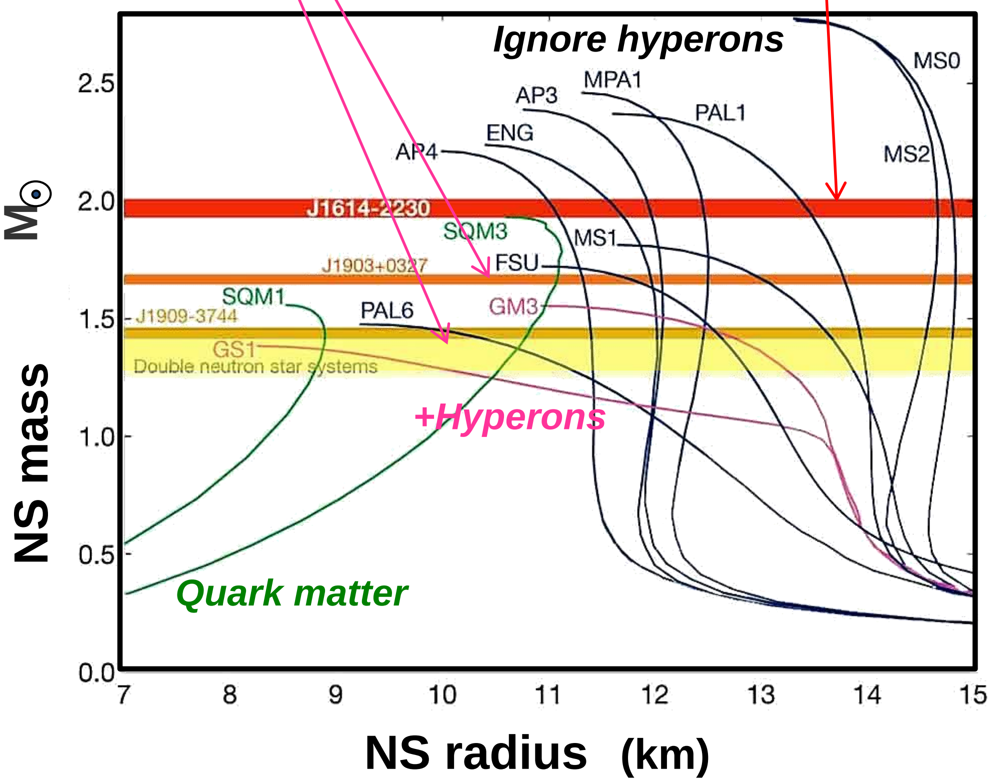
3-body force with hyerpons

"Hyperon puzzle" in neutron stars

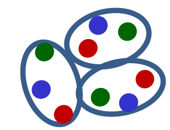
- Hyperons (Λ at least) <u>must appear</u> at $\rho \sim 2\,\rho_0$
- EOS's with hyperons or kaons too soft -> cannot support $M > 1.5\,M_{sun}$
- Heavy NS's (~$2.0\,M_{sun}$) were observed.

=> Unknown repulsion at high ρ

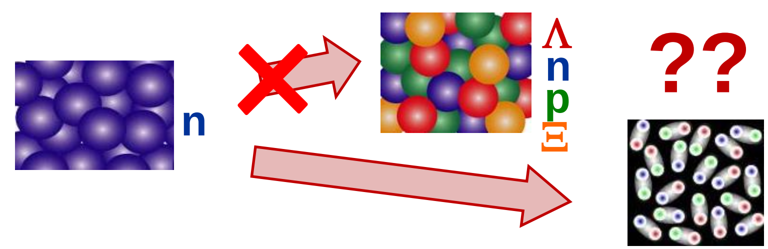
PSR J1614-2230 (2010) $1.97 \pm 0.04\,M_{sun}$
PSR J0348-0432 (2013) $2.01 \pm 0.04\,M_{sun}$



- Strong repulsion in three-body force including hyperons, NNN, YNN, YYN, YYY ?

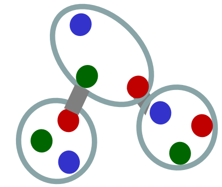


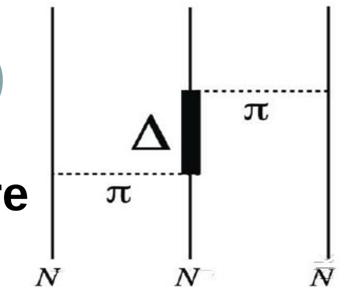
- Phase transition to quark matter ? (quark star or hybrid star)



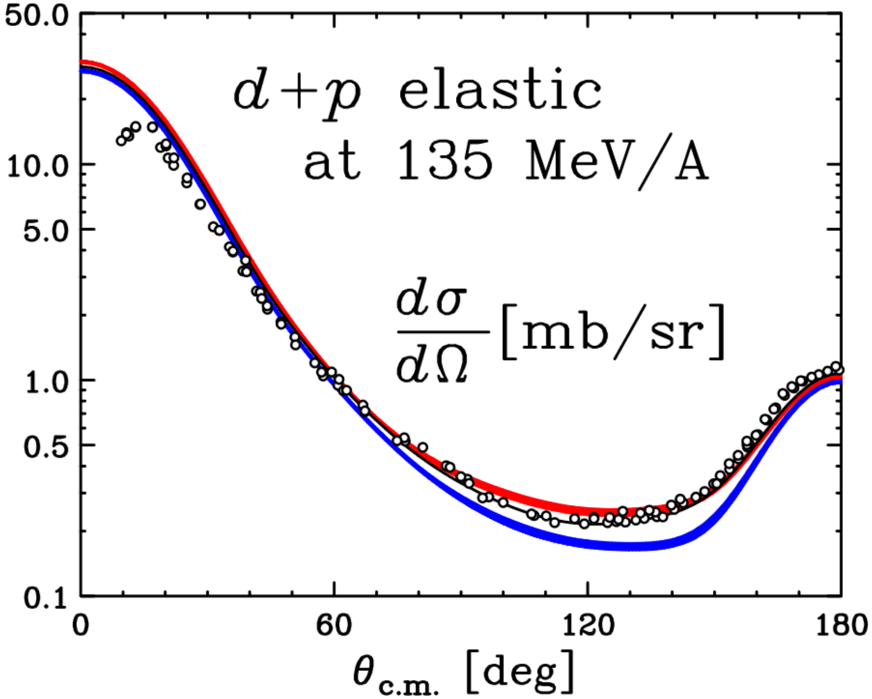
We need to know YN, YY, $K^{bar}N$ interactions both in free space and <u>in nuclear medium</u>

3-body nuclear force (NNN)





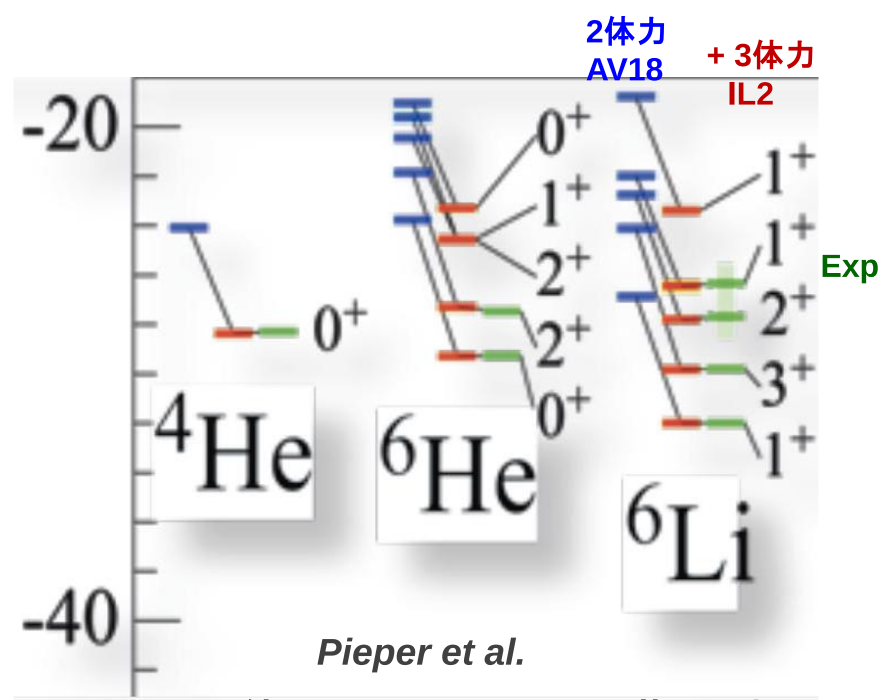
Hadron has internal structure
-> 3-body force may exist



K. Sekiguchi *et al.*, Phys. Rev. C **65**, 034003 (2002)

NN(CD Bonn, AV18, Nijimegen I,II)
3NF(TM'99)+NN
3NF(Urbana IX)+NN(AV18)

･Attractive for light (small ρ) nuclei
Fujita-Miyazawa type

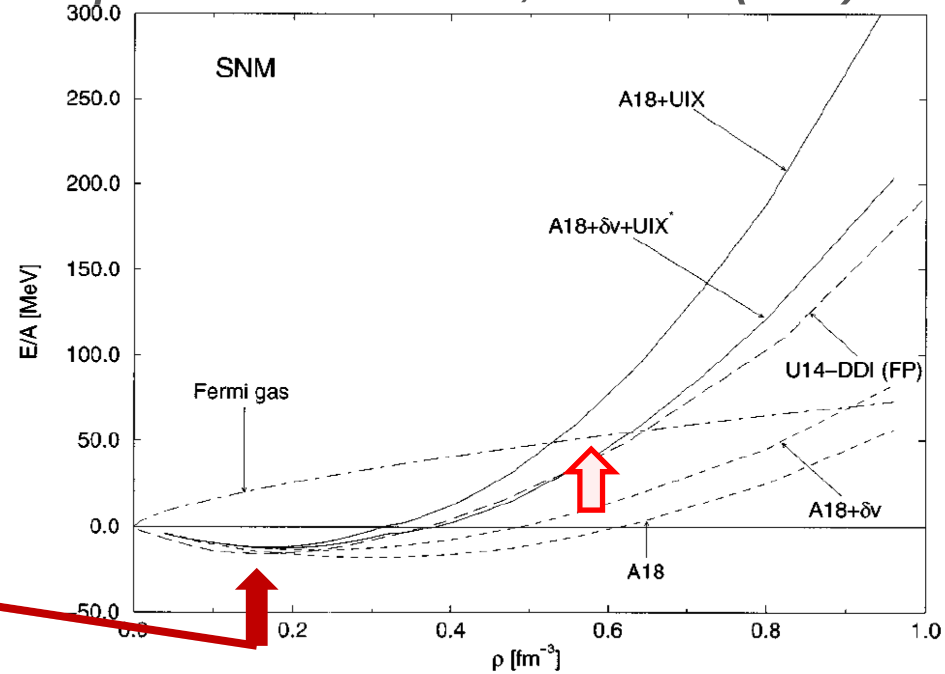


Illinois型3体力（2π exchange, 藤田・宮沢型）

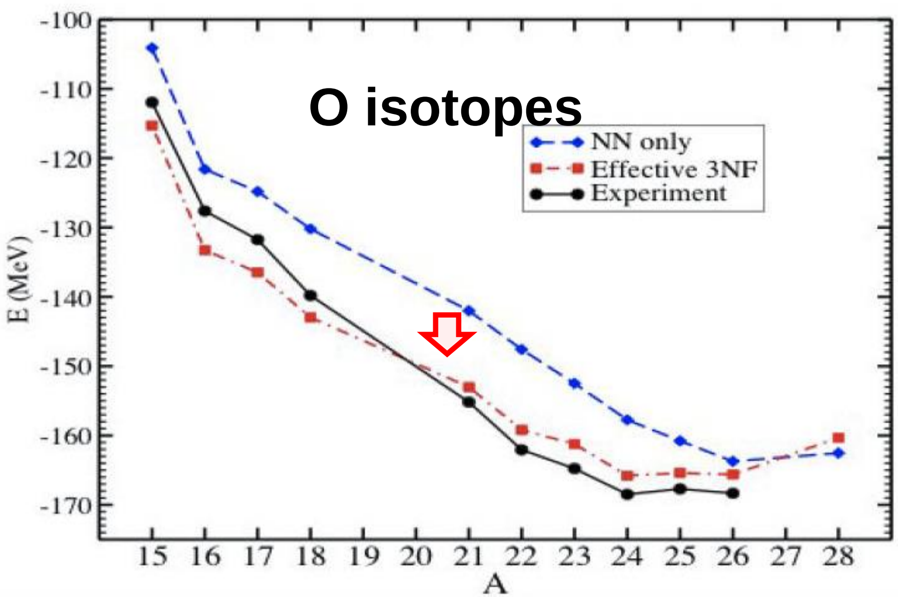
Akmal, Pandharipande and Ravenhall, PRC 58 (1998) 1804

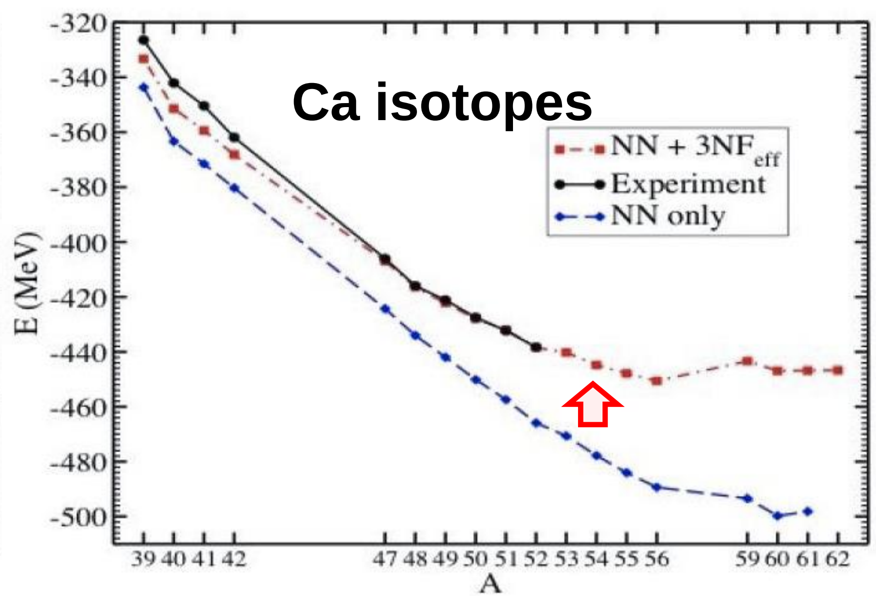
3-body nuclear force

3-body nuclear force should be repulsive at high density ($\rho \gtrsim \rho_0$)



Saturation point (ρ_0) is reproduced with 3BF.



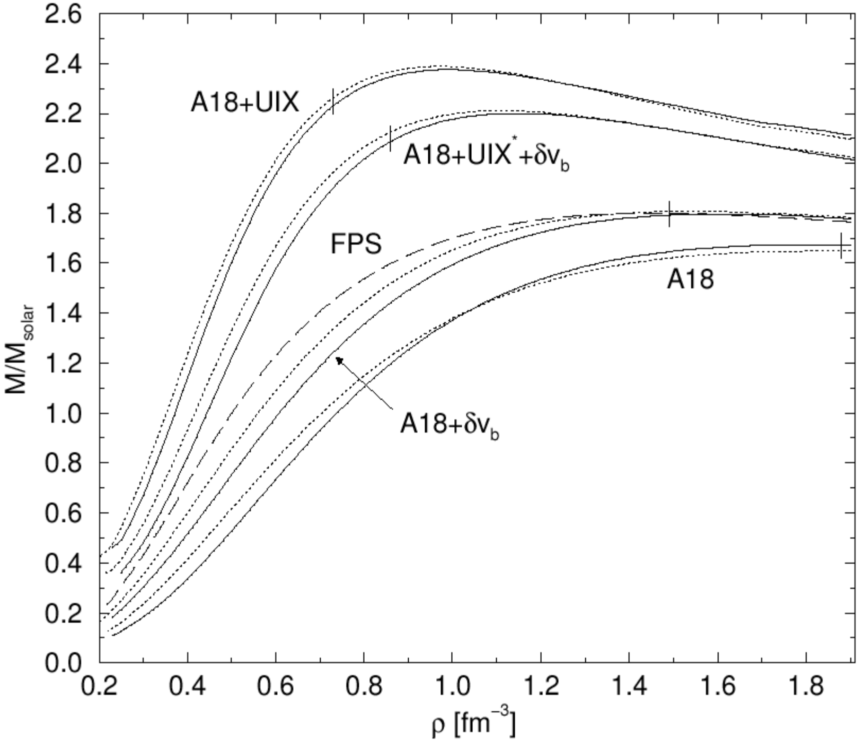


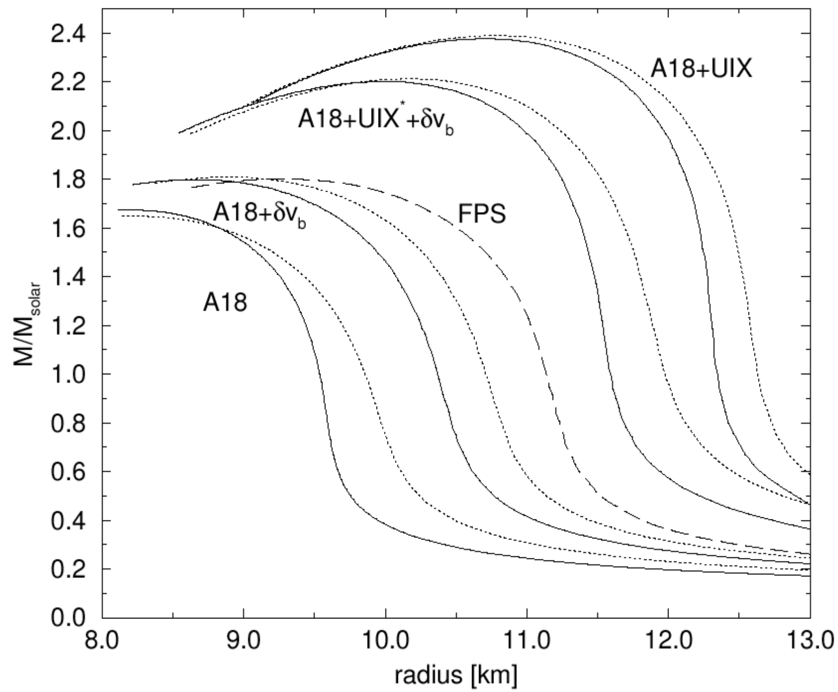
Chiral effective field theoryによる3体力

G. Hagen et al., PRL 109 (2012) 032502

3BF makes EOS of NS stiffer

UIX: Urbana type 3BF **δv_b : relativistic effect**





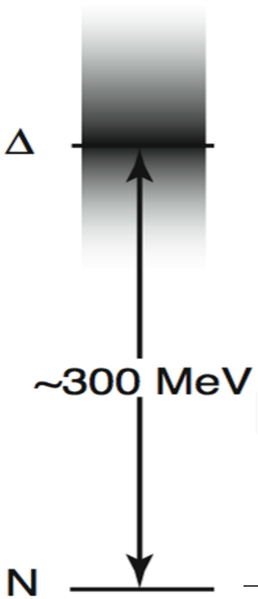
Akmal, Pandharipande and Ravenhall, PRC 58 (1998) 1804

Max NS mass = 1.6M⊚ (only 2BF)

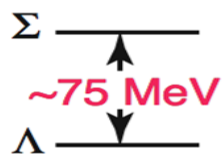
Max NS mass = 2.2 M⊚ (+ 3BF)

No hyperons in this calculation

Baryon mixing and three-body force in hypernuclei

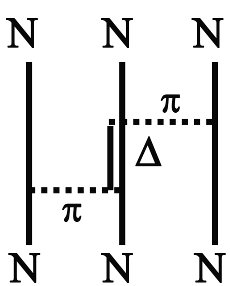


Mixing ∝ 1/*ΔE*
-> Large Σ mixing (~a few % ?)

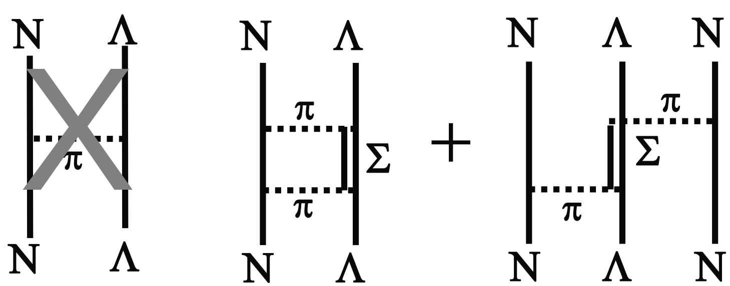


πN□ πN, Δ □ πN : experimentally known
πΛ □ πΛ, Σ □ πΛ : not known – theoretical (SU(3)$_f$) input necessary

S = 0



S = -1



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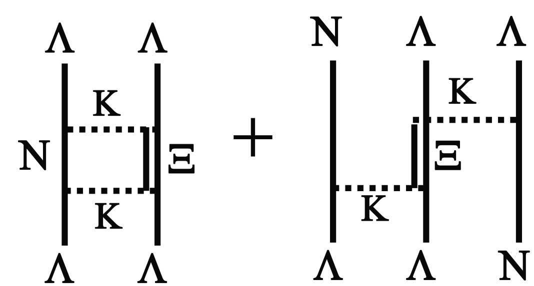
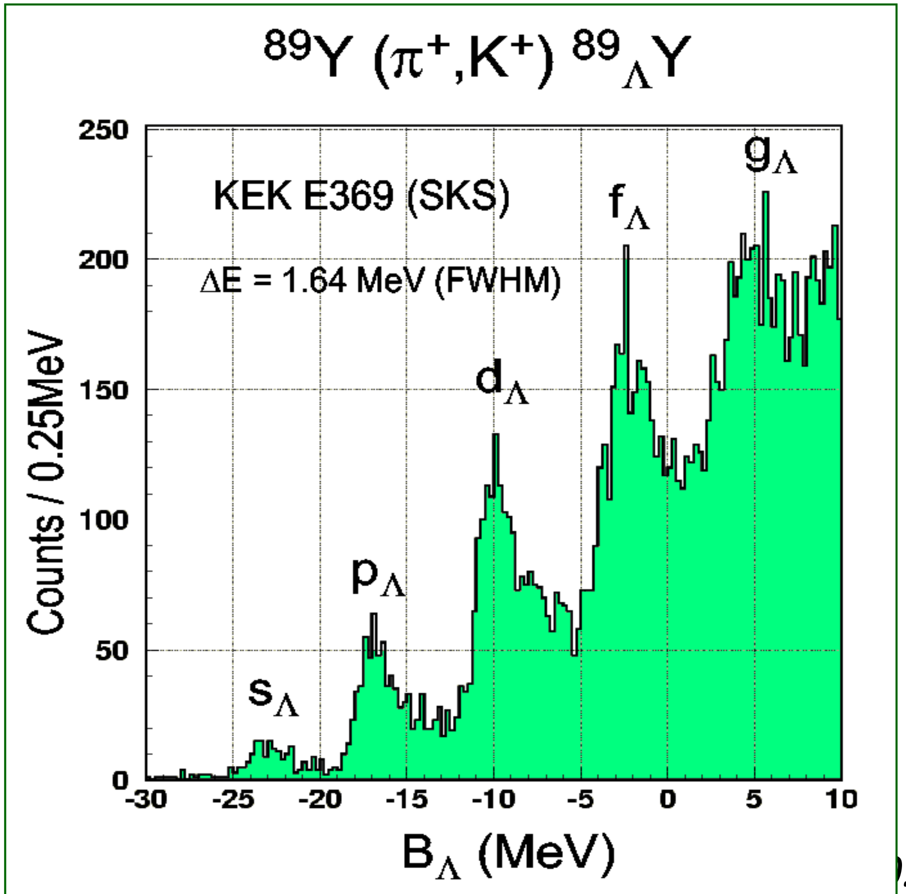


Λ's binding energy and the max mass of neutron stars

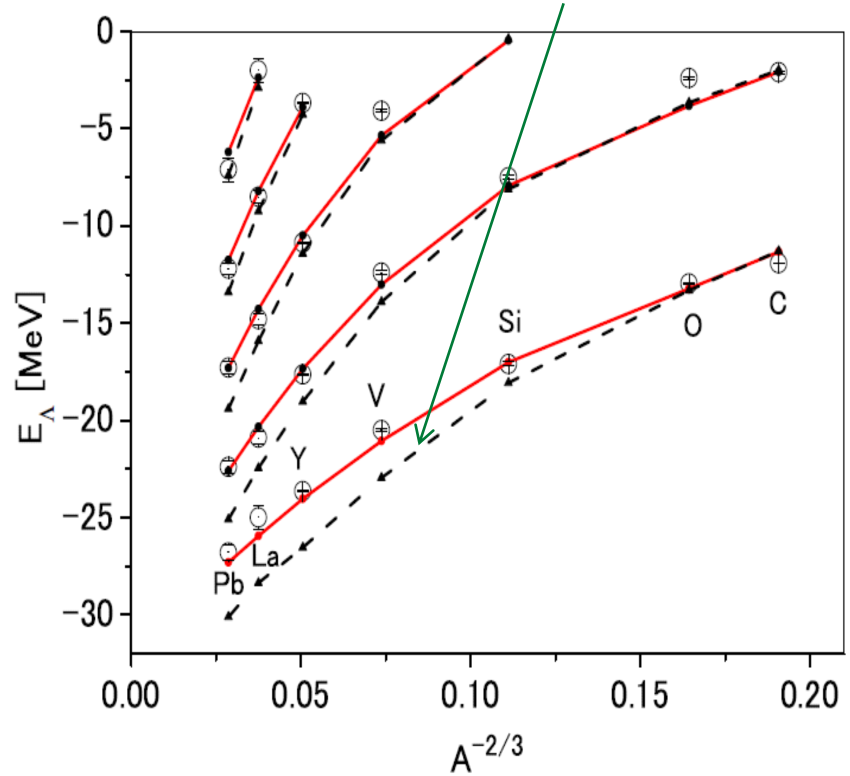
Nijmegen ESC08 int: almost all hypernuclear data
+YN scattring data are reproduced.

Y. Yamamoto et al.
PRC 88 (2013) 2, 022801
PRC 90 (2014) 4, 045805

"3B/4B repulsion: assumed to be the same between NNN and YNN, YYN.
Fix 3B/4B repulsive force strength using $^{16}O+^{16}O$ collision data
("universal 3B repulsion").



w/o and w/ 3B+4B repulsion in YNN
different slope



.1 MeV) data of Λ biding energies are necessary

Extension Plans of J-PARC Hadron Hall

S= -1 Systems

γ-ray spectroscopy
weak decays
ΛN scattering

- < 1.2 GeV/c
- ~10^6 K^-/spill

High precision
Λ hypernuclear spectroscopy

- < 2.0 GeV/c
- 1.8x10^8 pion/spill
- x10 better Δp/p

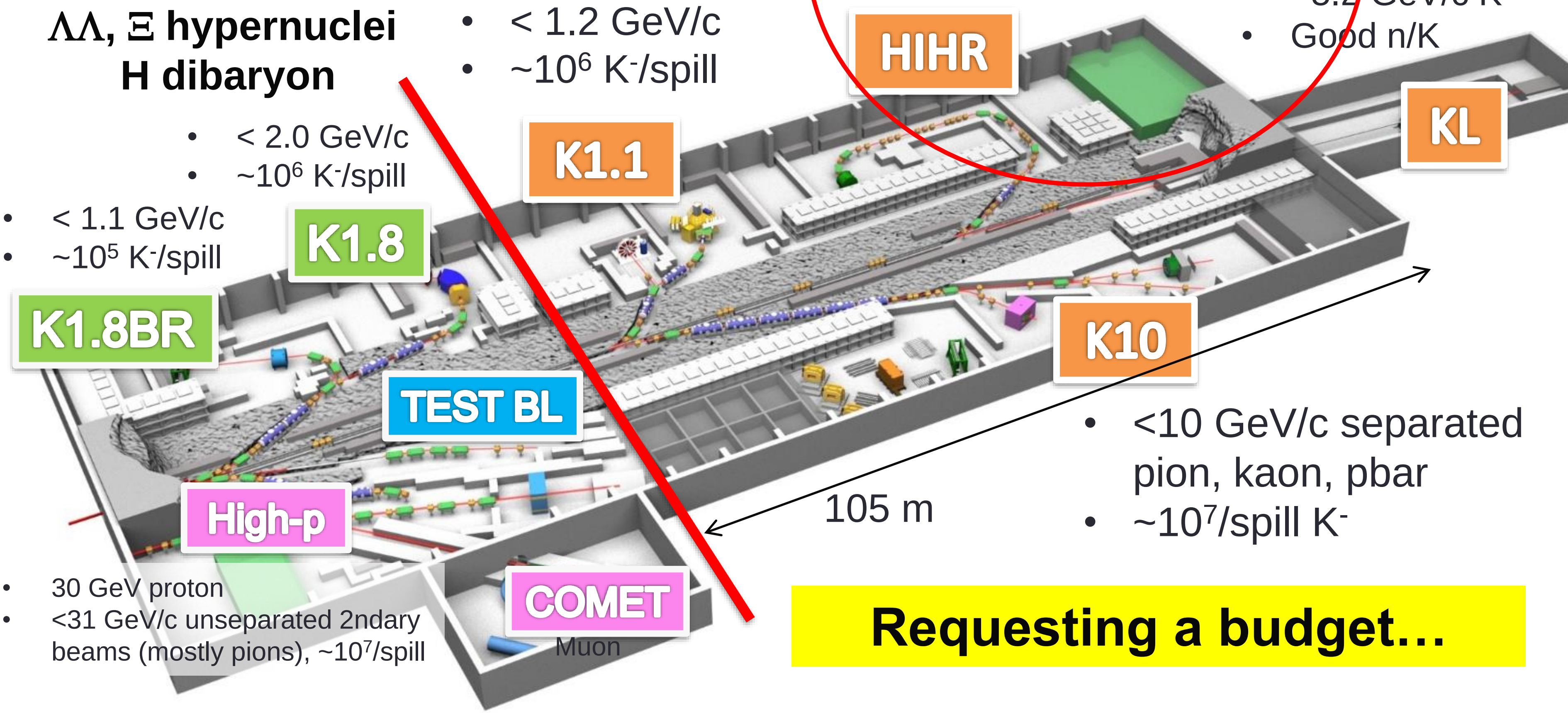
- 5 deg extraction
- ~5.2 GeV/c K^0
- Good n/K

S= -2 Systems

ΛΛ, Ξ hypernuclei
H dibaryon

- < 2.0 GeV/c
- ~10^6 K^-/spill

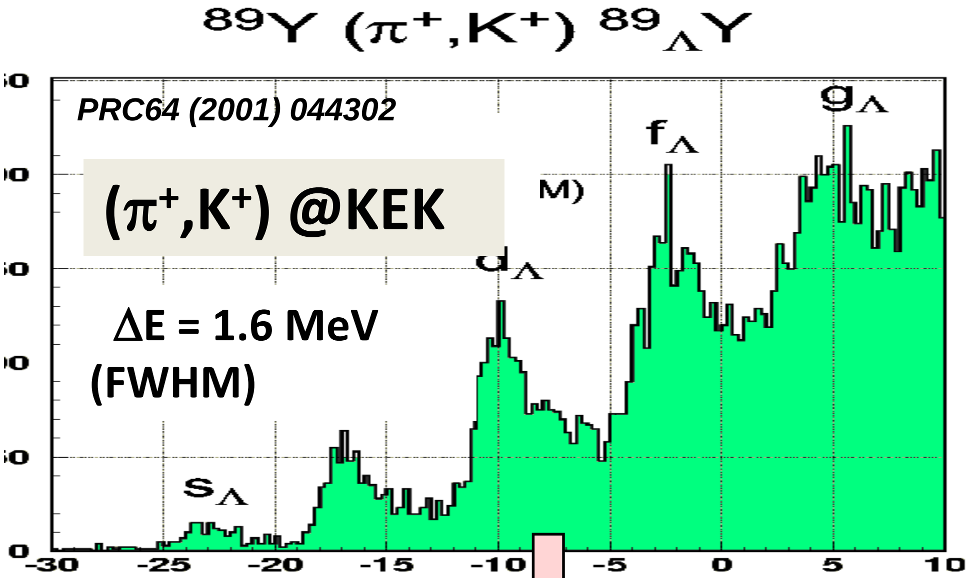
- < 1.1 GeV/c
- ~10^5 K^-/spill

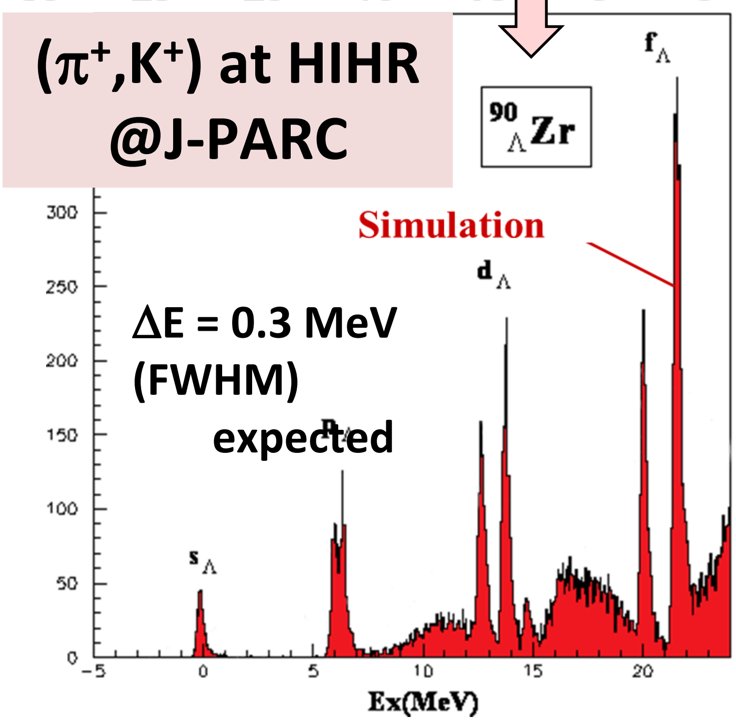


- <10 GeV/c separated pion, kaon, pbar
- ~10^7/spill K^-

- 30 GeV proton
- <31 GeV/c unseparated 2ndary beams (mostly pions), ~10^7/spill

Requesting a budget…





PARC Hadron Hall

High precision
Λ hypernuclear spectroscopy

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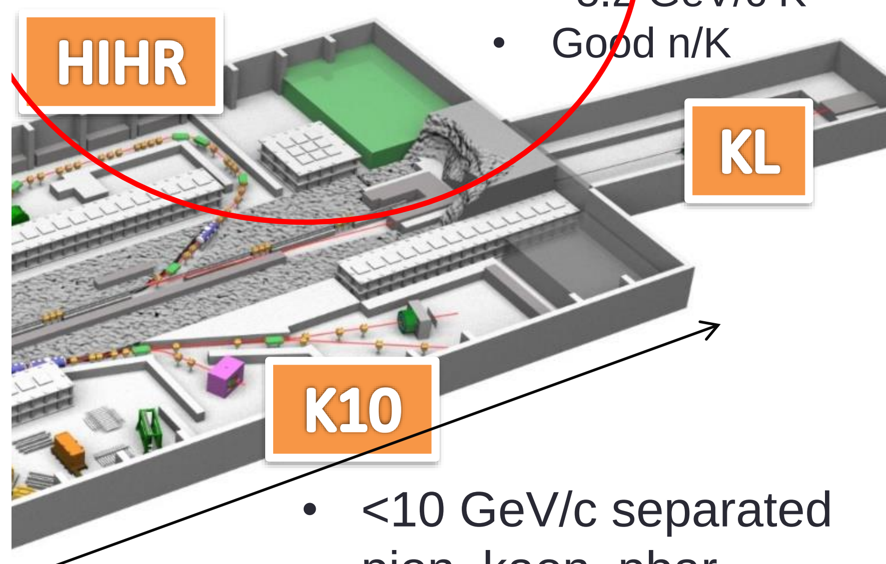

- <10 GeV/c separated pion, kaon, pbar
- ~10^7/spill K^-

Requesting a budget…

Summary

1 . Why is hierarchy of matter born?

- **Cluster formation by strong force with saturation of “charge”.**
- **Strong repulsion between the clusters at short distance**
- **Weak attraction between the clusters at long distance**

  -> “Nucleus” cannot make a higher hierarchy

2. Nuclear force (baryon-baryon interactions)

- **Meson exchanges at long distances, quark Pauli effect and color magnetic interaction at short distances**

  -- to be confirmed by experiments with strangeness

3. BB interactions with strangeness

- **Various hypernuclear data have been used to construct and test the BB interaction models.**
- **Key experiments: Σp scattering and H dibaryon search**
- **YNN 3-body force has to be also investigated.**

Missing today: chiral EFT, meson-nucleus molecule(K^-pp)