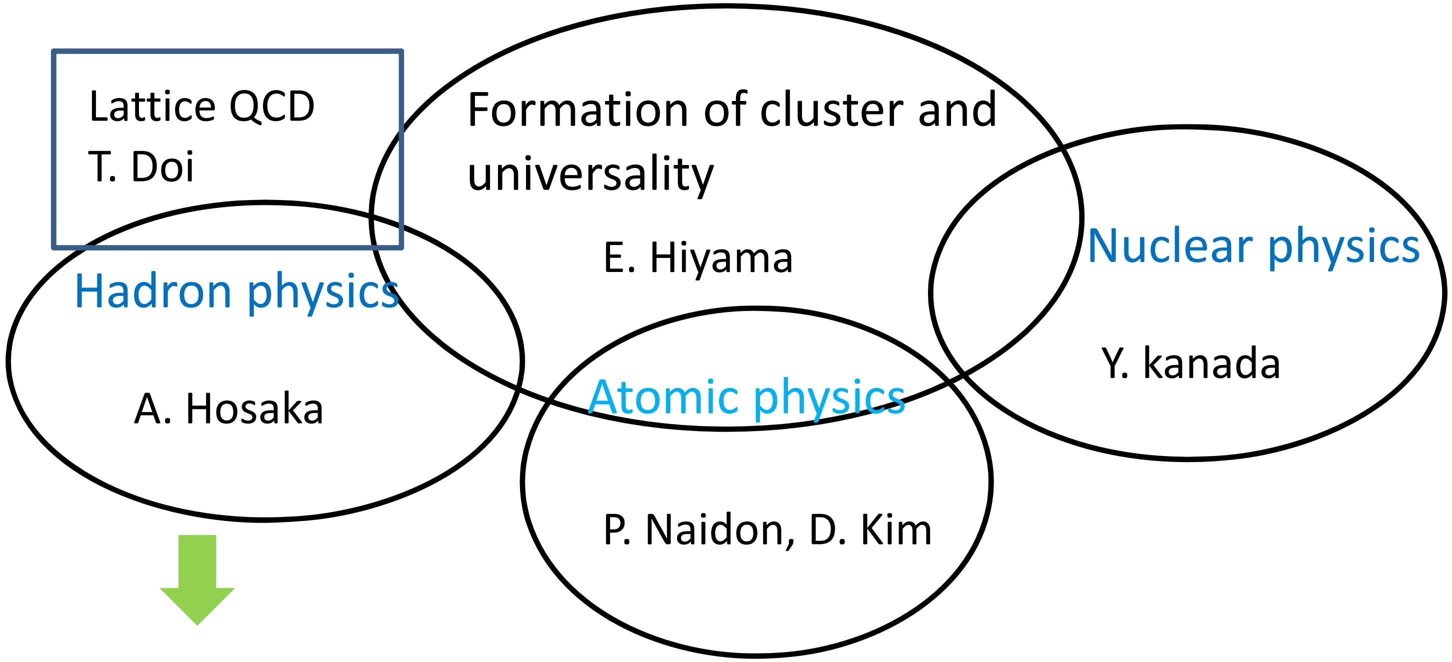
Structure of few-body exotic systems

Emiko Hiyama (Kyushu Univ./RIKEN)

Project by D-group



Talked by Hosaka

I report our research activities in other subjects within a few years.

Key words:

EOS： EOS based on Lattice QCD

Three-body force, baryon-baryon interaction:

construction by LQCD、

three-body force in hypernuclei:$\Lambda N - \Sigma N$ couling

Tensor force: contribution of tensor force in neutron-rich nuclei

How to form cluster in neutron-rich nuclei and also

in exotic hadron system.

Di-quark, di-neutron correlation

Universality： ultra cold atomic system, neutron-rich nuclei

Within two years, we have been discussing among D-group.

Three-body force, Baryon-Baryon interaction

QCD interaction by HAL collaboration (Doi)

Ex : ΞN interaction

Structure of light Ξ hypernuclei (Hiyama)

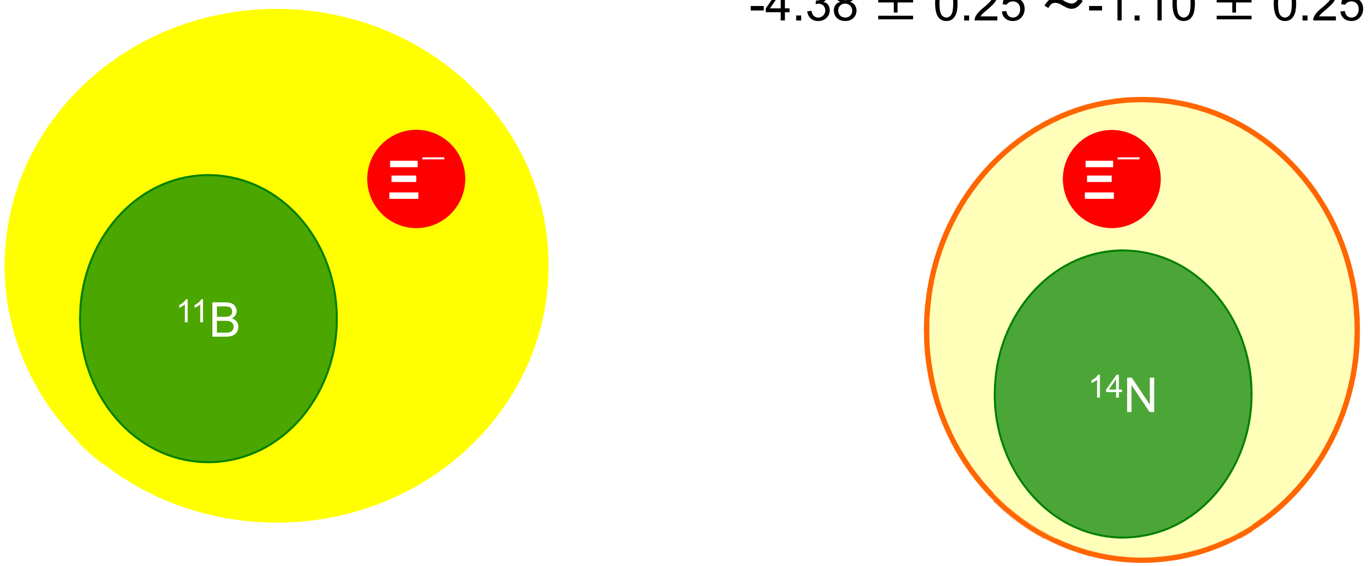
Contribution to B01-group: production of Ξ hypernuclei

$^{12}C(K^-,K^+)$, $^{7}Li(K^-,K^+)$

^{14}N-Ξ-

0 MeV

-4.38 ± 0.25 ～-1.10 ± 0.25 MeV



Kiso event

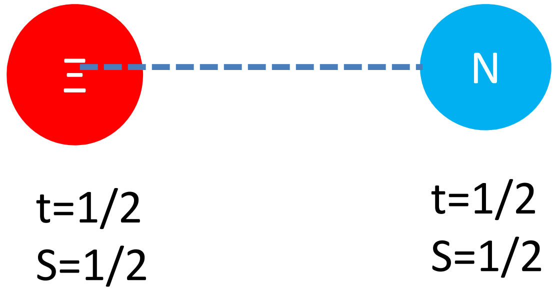
We have observed a few events for these Ξ hypernuclei.

$$V_{\Xi N} = V_0 + \boldsymbol{\sigma}\cdot\boldsymbol{\sigma}\, V_{\sigma\cdot\sigma} + \boldsymbol{\tau}\cdot\boldsymbol{\tau}\, V_{\tau\cdot\tau} + (\boldsymbol{\sigma}\cdot\boldsymbol{\sigma})(\boldsymbol{\tau}\cdot\boldsymbol{\tau})\, V_{\sigma\cdot\sigma\ \tau\cdot\tau}$$

$V_{\Xi N}$ interaction should be attractive.

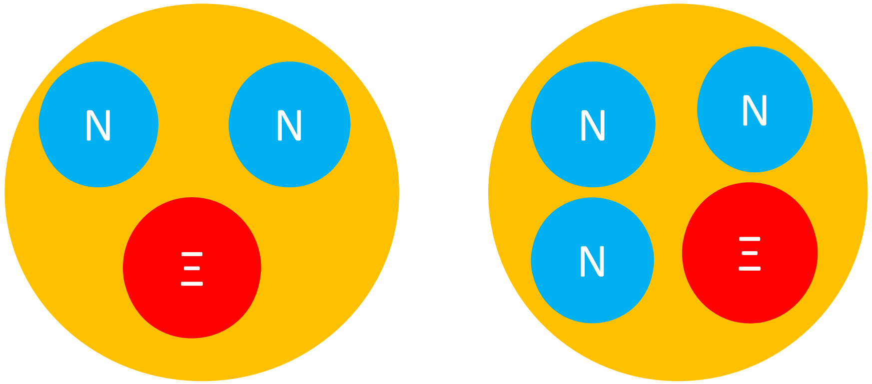
Important subject in Ξ hypernuclei

ΞN interaction: T=0, S=0
T=0, S=1
T=1, S=0
T=1, S=1



Four components should be attractive? Or repulsive?
To investigate it, what is best suited Ξ hypernuclei?

How do we produce Ξ hypernuclei？



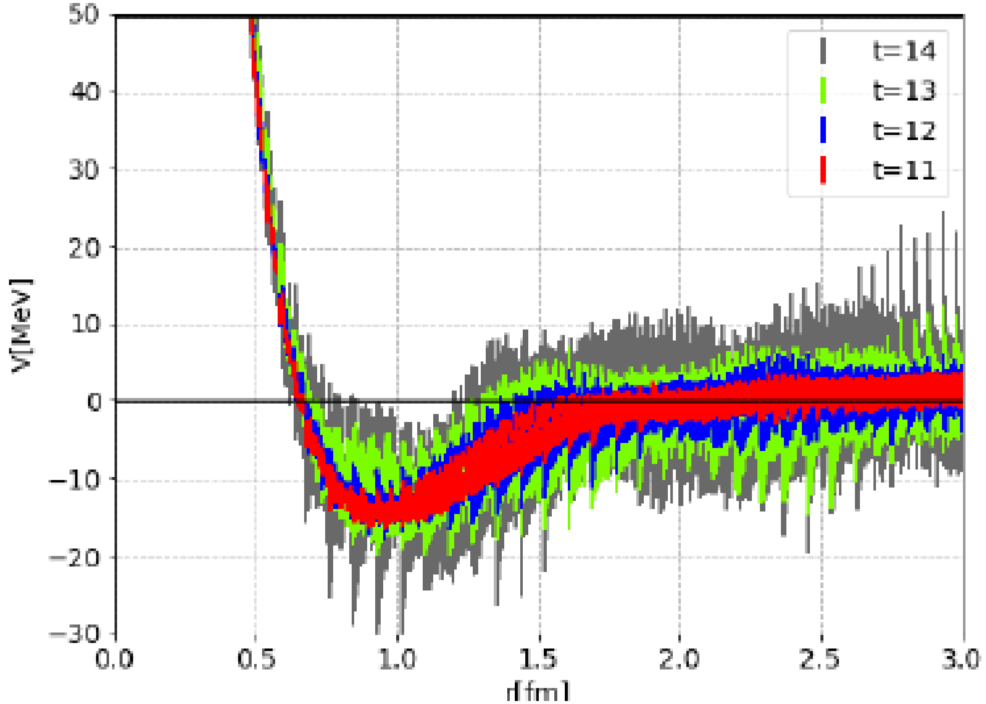
No data

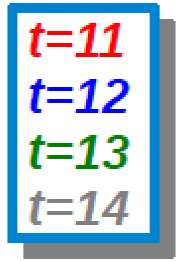
These s-shell Ξ hypernuclei is suited for obtaining (T,S)=(0,0), (0,1), (1,0) and (1,1).

To obtain (predict) the binding energies of these Ξ hypernuclei,
We should employ ‘reliable’ ΞN interaction.

We have ΞN potential models by Nijmegen group. However,
The models have a lot of ambiguity due to no ΞN scattering data and a few data on Ξ hypernuclei.

$$V_{N\Xi}(r) = V_0 1 + V_\sigma(\sigma\cdot\sigma) + V_\tau(\tau\cdot\tau) + V_{\sigma\tau}(\sigma\cdot\sigma)(\tau\cdot\tau)$$





ΞN interaction by HAL QCD collaboration

ΞN potential has been proposed by K. Sasaki and T. Doi et al.

Possible Lightest Ξ Hypernucleus with Modern Ξ*N* Interactions

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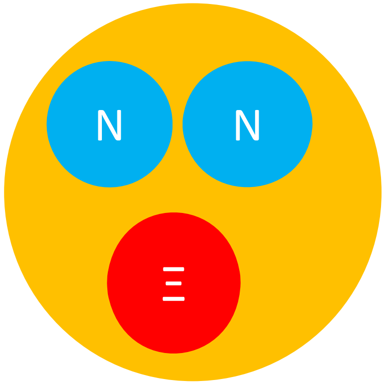
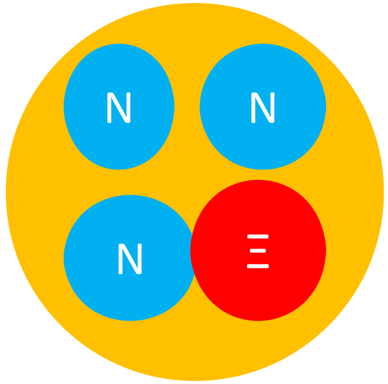
(Received 19 October 2019; revised manuscript received 18 January 2020; accepted 22 January 2020; published 4 March 2020)

Experimental evidence exists that the Ξ-nucleus interaction is attractive. We search for $NN\Xi$ and $NNN\Xi$ bound systems on the basis of the AV8 NN potential combined with either a phenomenological Nijmegen ΞN potential or a first principles HAL QCD ΞN potential. The binding energies of the three-body and four-body systems (below the $d + \Xi$ and ${}^3\mathrm{H}/{}^3\mathrm{He} + \Xi$ thresholds, respectively) are calculated by a high precision variational approach, the Gaussian expansion method. Although the two ΞN potentials have significantly different isospin (T) and spin (S) dependence, the $NNN\Xi$ system with quantum numbers ($T = 0$, $J^\pi = 1^+$) appears to be bound (one deep for Nijmegen and one shallow for HAL QCD) below the ${}^3\mathrm{H}/{}^3\mathrm{He} + \Xi$ threshold. Experimental implications for such a state are discussed.





I show my new results of these light systems.

NN interaction: AV8 potential

ΞN interaction :

Nijimegen extended soft core potential (ESC08c)

Realistic potential (only ΞN channel)

ΞN interaction by HAL collaboration (Lattice QCD calculation)

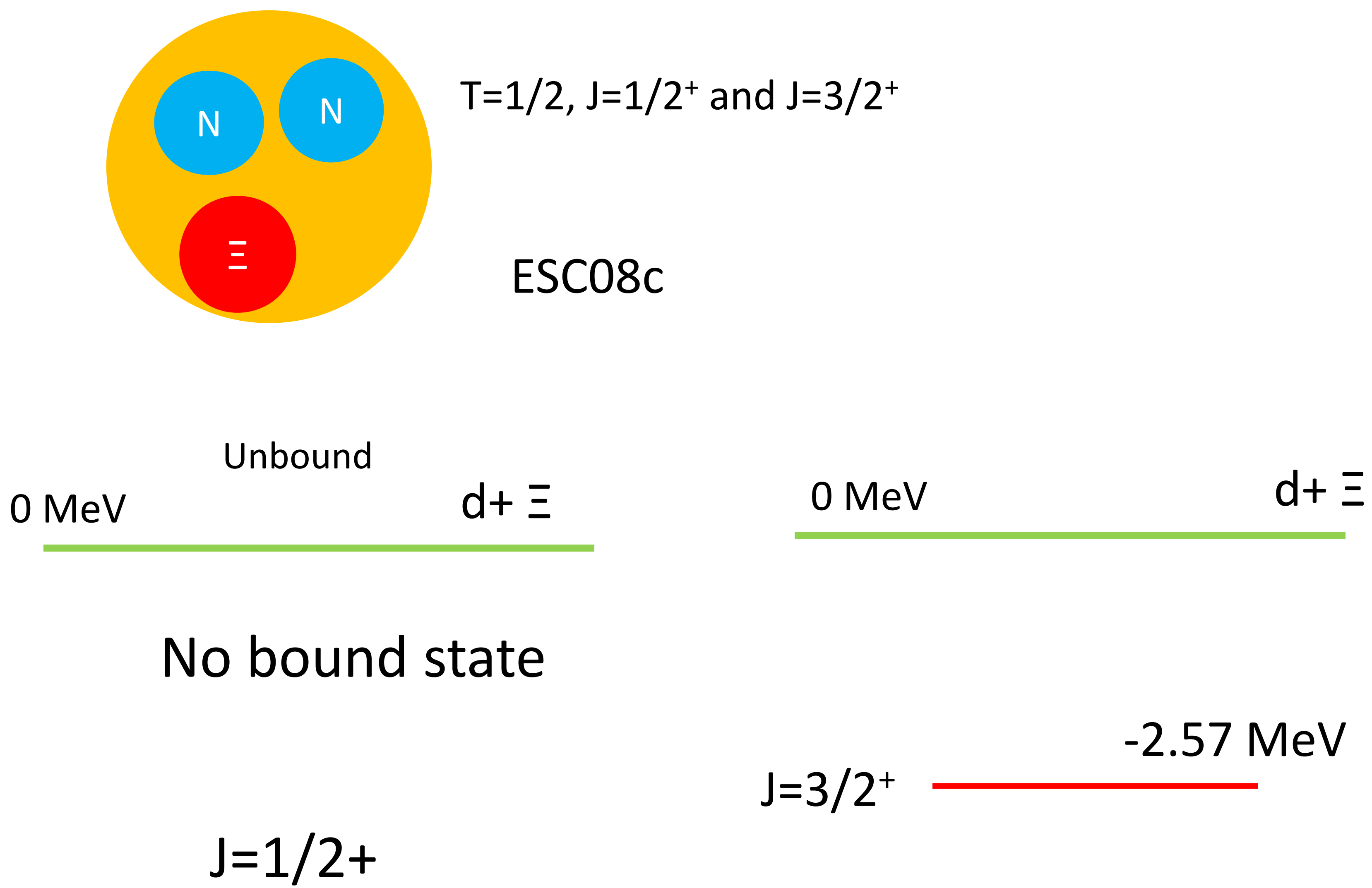
The potential was made by K. Sasaki and Miyamoto.

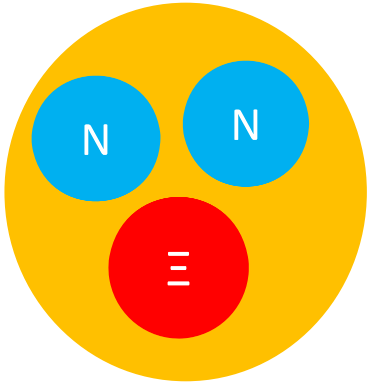
Property of the spin- and isospin-components of ESC08 and HAL

V(T,S)	ESC08c	HAL
T=0, S=1	strongly attractive	Weakly attractive
T=0, S=0	weakly repulsive	Strongly attractive
T=1, S=1	strong attractive	Weakly attractive
T=1, S=0	weakly repulsive	Weakly repulsive

Although the spin- and isospin-components of these two models are very different between them.

It is interesting to see the difference in the energy spectra in s-shell Ξ hypernuclei.


N
N
Ξ
T=1/2, J=1/2+ and J=3/2+
ESC08c
Unbound
0 MeV
d+ Ξ
No bound state
J=1/2+
0 MeV
d+ Ξ
-2.57 MeV
J=3/2+



T=1/2, J=1/2$^+$ and J=3/2$^+$

HAL potential

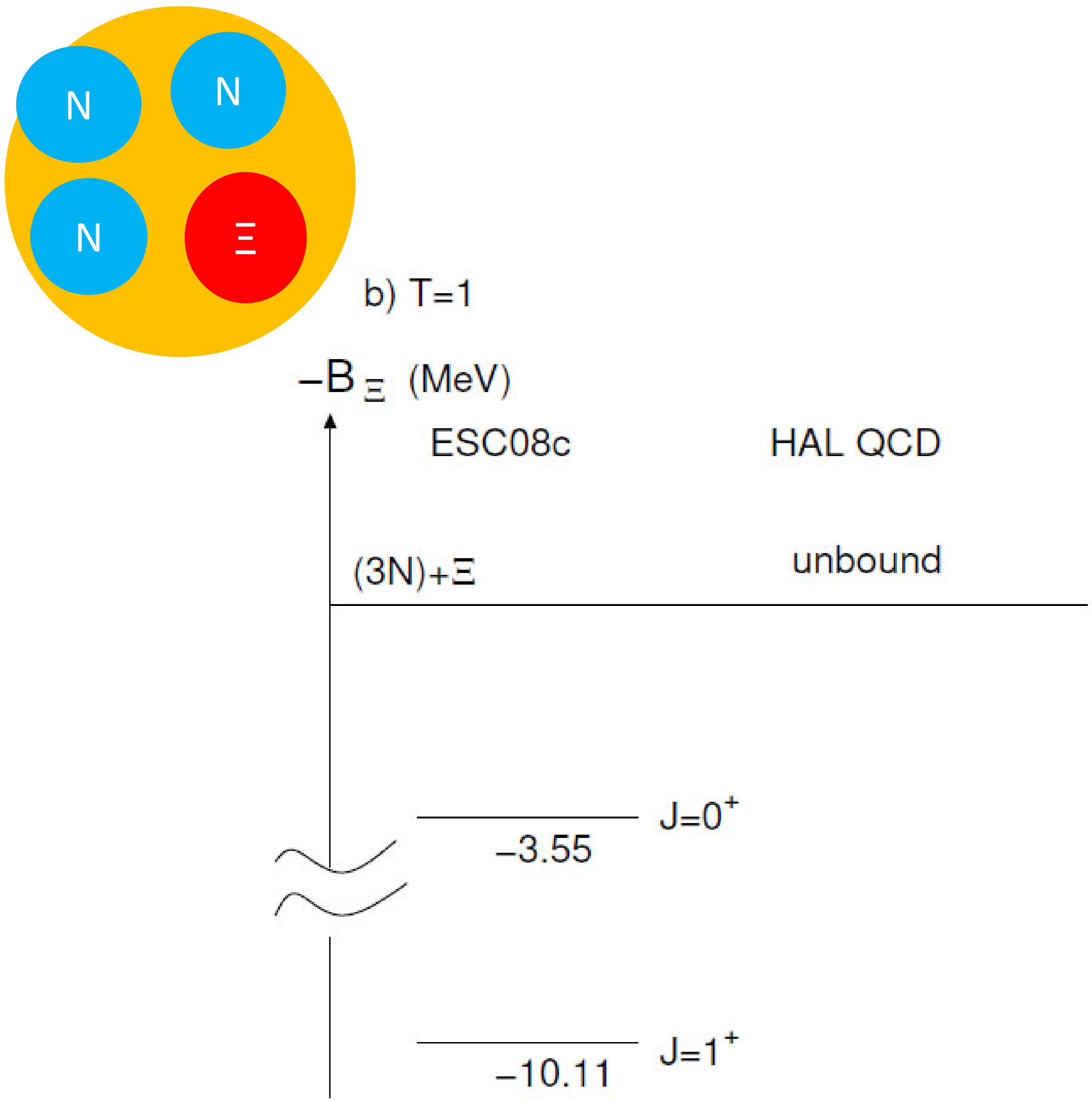
0 MeV d+ Ξ

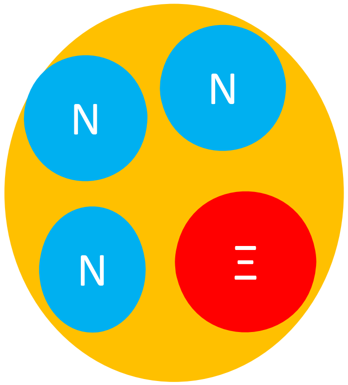
0 MeV d+ Ξ

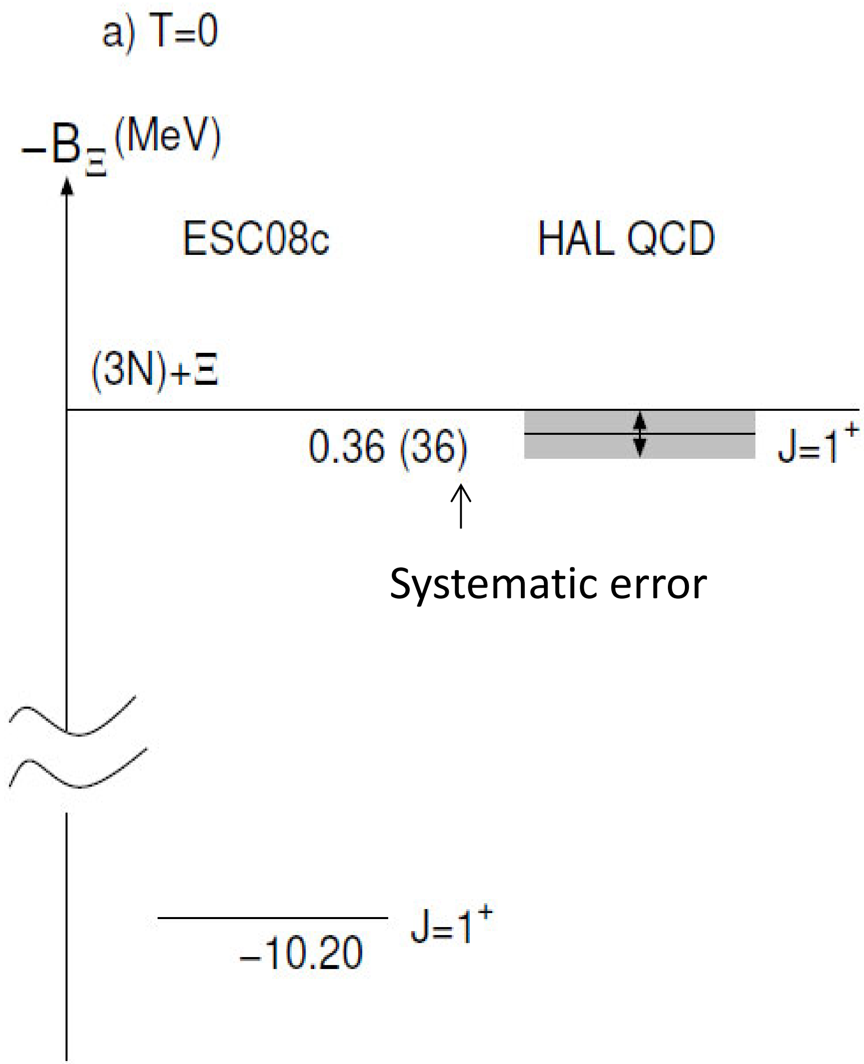
No bound state

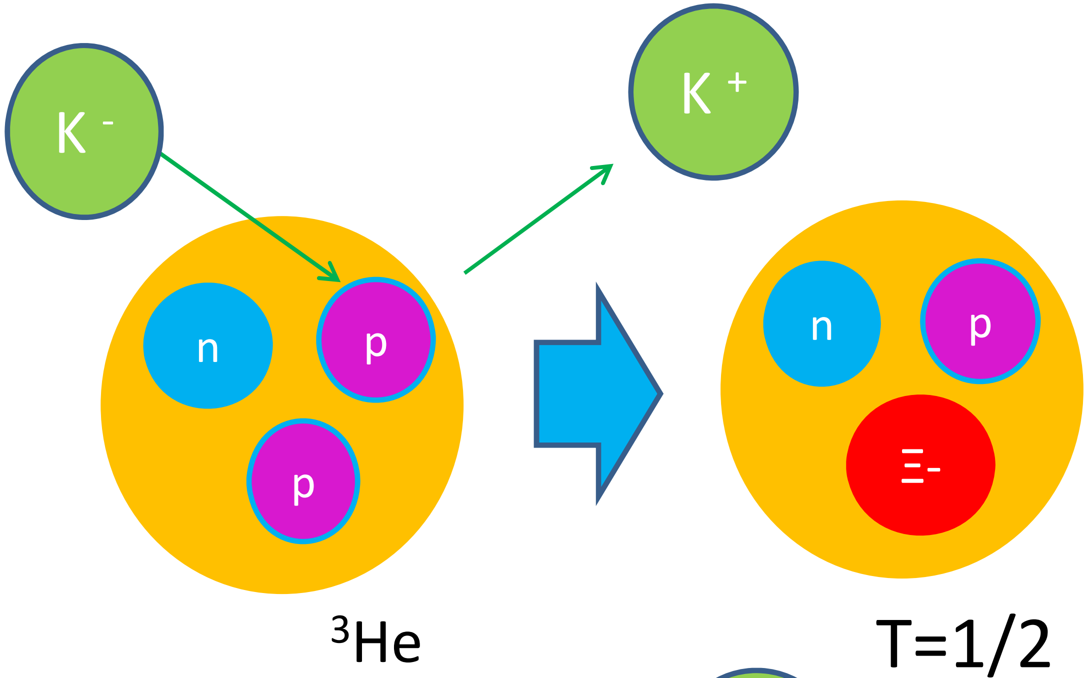
J=3/2$^+$

J=1/2+


N
N
N
Ξ
b) T=1
−B Ξ (MeV)
ESC08c
HAL QCD
(3N)+Ξ
unbound
J=0+
−3.55
J=1+
−10.11


N
N
N
Ξ

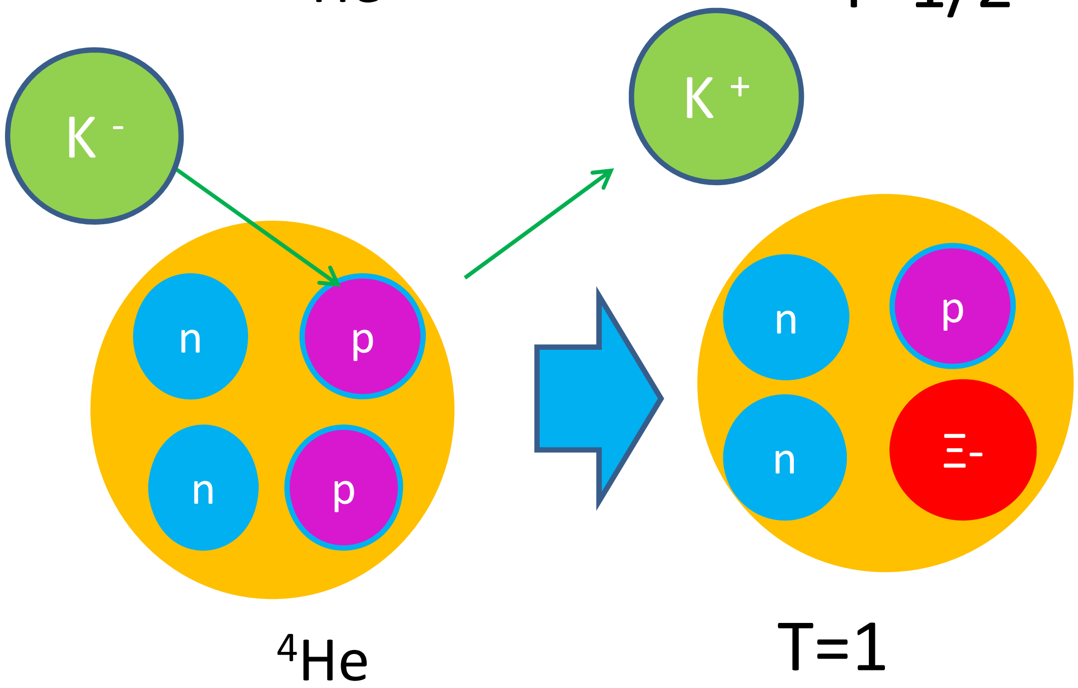

a) T=0
$-B_{\Xi}$ (MeV)
ESC08c
HAL QCD
(3N)+Ξ
0.36 (36)
$J=1^+$
Systematic error
-10.20
$J=1^+$



How do we produce them?

(K^-,K^+) reaction by ^{3}He and ^{4}He targets at J-PARC

Heavy ion reaction at Alice?
or another facility?



理化学研究所 RIKEN

RIKENメルマガ 検索

Press Release (March 5, 2020)

2020年3月5日

理化学研究所
九州大学
京都大学

新たなハイパー原子核「グザイ・テトラバリオン」

－グザイ粒子の振る舞いを精密計算で解き明かす－

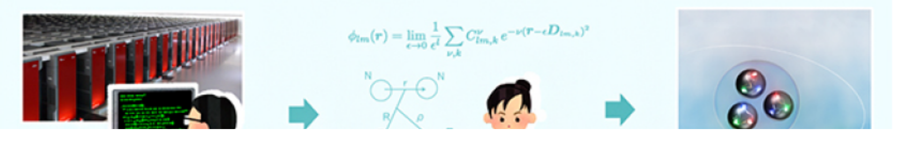
理化学研究所（理研）仁科加速器科学研究センターストレンジネス核物理研究室の肥山詠美子室長（九州大学大学院理学研究院教授）、量子ハドロン物理学研究室の土井琢身専任研究員、理研数理創造プログラムの初田哲男プログラムディレクター、京都大学基礎物理学研究所の佐々木健志特任助教らの国際共同研究グループは、グザイ粒子[1]1個と核子[2]3個からなる新たなハイパー原子核（ハイパー核）[3]「グザイ・テトラバリオン」の存在を理論的に予言しました。

本研究成果は、どのようなハイパー核が存在しうるのかという物理学の根源的問題の解明につながるとともに、中性子星[4]内部のような超高密度極限状態における物質構造の解明に貢献すると期待できます。

通常の原子核は核子というバリオン[5]から構成されていますが、グザイ（Ξ）粒子と核子からなるハイパー核については、どのような種類のものが存在するかほとんど分かっていませんでした。

今回、国際共同研究グループは、クォーク[6]の基礎理論「量子色力学（QCD）」[7]に基づき、グザイ粒子と核子の間に働く力をスーパーコンピュータ「京」[8]などを用いて明らかにしました。さらに、得られた力をもとに量子少数多体系[9]の精密計算を行うことで、グザイ粒子1個と核子3個の計4個のバリオンからなる新たなハイパー核「グザイ・テトラバリオン」の存在を予言しました。

本研究は、科学雑誌『*Physical Review Letters*』の掲載に先立ち、オンライン版（3月4日付）に掲載される予定です。



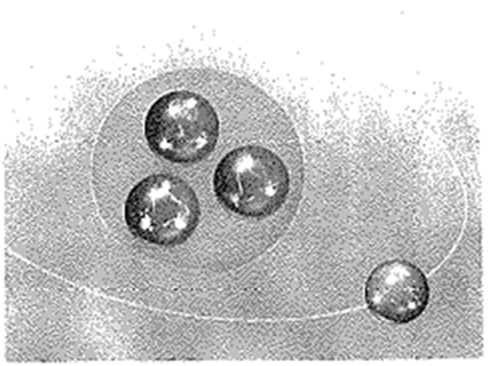
日刊工業新聞　　2020年3月6日（金）　朝刊　29 面

新粒子の存在予言

極限状態の物質 解明期待

理研など

理化学研究所や九州大学、京都大学などの国際研究グループは、素粒子の一種「ストレンジクォーク」を含む新しい粒子の存在を理論的に予言した。素粒子の基礎理論を基に、ストレンジクォークを2個含む「グザイ粒子」と陽子や中性子などの「核子」の間に働く力をスーパーコンピューター「京」で計算。得られた力を基に精密計算を実施し、グザイ粒子1個と核子3個からなる粒子「グザイ・テトラバリオン」の存在を予言した。



グザイ・テトラバリオンのイメージ（理研提供）

グザイ粒子と核子の間に働く力は、超新星爆発の後に中性子星かブラックホールのどちらができるかを決める要素と考えられている。中性子星内部のような超高密度極限状態での物質構造の解明につながると期待される。

グザイ粒子と核子からなる「ハイパー核」は、どのような種類が存在するかほとんど分かっていなかった。研究グループは、計算の高速化アルゴリズムやスパコンを利用した大規模数値シミュレーションを実施し、グザイ粒子と核子の間に働く力を解析。各粒子の状態に応じ、2粒子の間の力が引力や斥力に変わることが分かった。

さらにグザイ粒子1個に対し核子の個数を増やしながら計算。核子の数が3個の場合、グザイ粒子と核子の間の引力と斥力が絶妙のバランスで安定した新しいグザイ・ハイパー核が存在することを明らかにした。

成果は5日、米科学誌フィジカル・レビュー・レターズ電子版に掲載された。

Equation of State (EOS) By Togashi

EOS based on Lattice QCD

- Higher partial wave interactions
- Three-baryon interactions

are also need.

Baryon Interaction by LQCD（Doi）

- Flavor SU(3) symmetry
- Only s-wave baryon-baryon interactions

EOS by the variational method with coupled-channel interactions

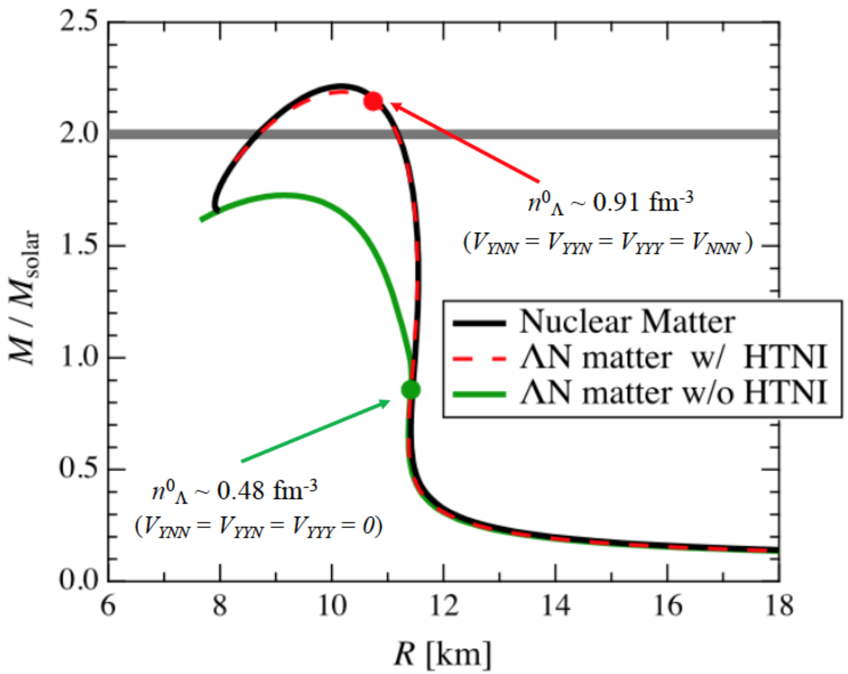
Application to Neutron Stars (Togashi)

EOS based on Lattice QCD

- **Baryon-baryon interactions by Lattice QCD**
- **Coupled-channel interactions are provided explicitly**

(T. Inoue et al., AIP Conf. Proc. 2130 (2019) 020002)

The cluster variational method is reformulated in second quantization in order to treat hyperons as quasi-particles in the Jastrow wave function.



Neutron Star with Λ hyperons

- Hyperon three-body interaction (HTNI) is added to reproduce $2M_\odot$ neutron stars.
- We try to take into account the mixing of all hyperons. (Λ, Σ^-, Σ^0, Σ^+, Ξ^0, Ξ^-)

Three-body force: this is important to subject.
in B02 (talked by Sekiguchi san)

Especially it is interesting to investigate study of T=3/2 three-body force

For the study of three-body force, tetra-neutron system is suited.
However, it is difficult to conclude whether or not to exist this system.

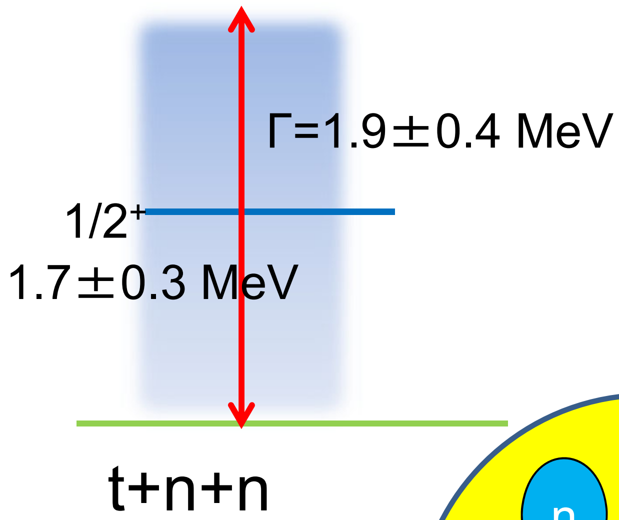
Second candidate : ^{5}H

Further investigation of T=3/2 force and existence of tetra neutron syster

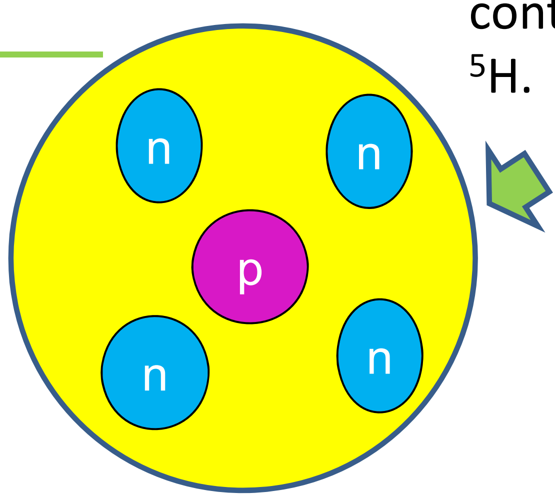
structure of ^{5}H and ^{7}H is one of good candidate.

transfer reaction p(^{6}He, ^{2}He)^{5}H

A. A. Korcheninnikov, et al. Phys. Rev. Lett. 87 (2001) 092501.



T=3/2 and T=1/2 three-body forces contribute to the energies of ^{5}H. 4n+p



(E_R, Γ_R) (MeV)	
J^π	$1/2^+$
^{5}H (full)	(1.57, 1.53)
^{5}H ($d = 0$)	(1.55, 1.35)
Theor. [16]	(2.26, 2.93)
Theor. [12]	(2.5–3.0, 3–4)
Theor. [13]	(3.0–3.2, 1–4)
Theor. [15]	(1.59, 2.48)
Exp. [3]	(1.7 ± 0.3, 1.9 ± 0.4)
Exp. [8]	(1.8 ± 0.1, < 0.5)
Exp. [4]	(1.8, 1.3)
Exp. [5]	(2, 2.5)
Exp. [6]	(3, 6)
Exp. [9]	(5.5 ± 0.2, 5.4 ± 0.6)

Recent exp. Data:
A.H. Wuousmaa et al.,
PRC95 014310 (2017).
(2.4 ±0.3, 5.3±0.4)

We cited this experiment.
However, you have many
different decay widths.

[3] A.A. Korosheninnikov et al., PRL87 (2001) 092501
[8] S.I. Sidorchuk et al., NPA719 (2003) 13
[4] M.S. Golovkov et al. PRC 72 (2005) 064612
[5] G. M. Ter-Akopian et al., Eur. Phys. J A25 (2005) 315.

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www.elsevier.com/locate/physletb

Ab initio calculations of ^{5}H resonant states

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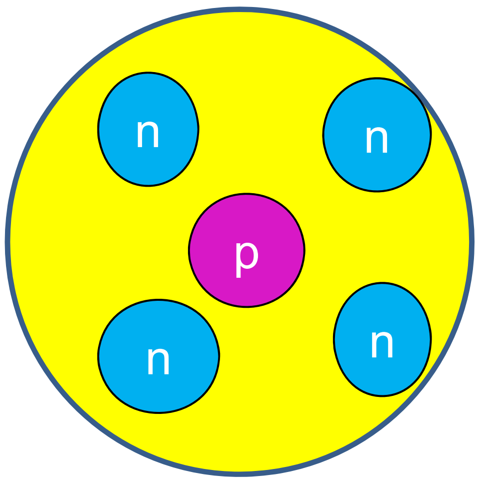
Ab initio calculations

ABSTRACT

By solving the 5-body Faddeev-Yakubovsky equations in configuration space with realistic nuclear Hamiltonians we have studied the resonant states of ^{5}H isotope. Two different methods, allowing to bypass the exponentially diverging boundary conditions, have been employed providing consistent results. The existence of ^{5}H broad J^π=1/2$^+$,3/2$^+$,5/2$^+$ states as S-matrix poles has been confirmed and compared with the, also calculated, resonant states in ^{4}H isotope. We have established that the positions of these resonances only mildly depend on the nuclear interaction model.

Two-body nuclear force
Can reproduce the data of
^{5}H?? No three-body force??

Another system, ^{7}H
The calculation is
on going.



		J=1/2$^+$		J=3/2$^+$		J=5/2$^+$	
		E_R	Γ	E_R	Γ	E_R	Γ
N3LO	$(ACCC)$	1.8(1)	2.4(2)				
	$(SECSM)$	1.9(2)	2.4(2)				
INOY	$(ACCC)$	1.7(1)	2.4(2)				
	$(SECSM)$	1.8(1)	2.4(2)				
MT13	$(ACCC)$	1.4(1)	2.4(2)				
	$(SECSM)$	1.7(2)	2.4(2)	2.5(2)	3.8(4)	2.5(2)	3.8(4)
[6] tnn		2.75(25)	3.5(5)	6.6(3)	8	4.8(2)	5
[15] RGM		3.1(1)	2.5(15)				
[20] RGM		1.59	2.48	3.0	4.8	2.9	4.1
[10] tnn		1.57	1.53	3.25	3.89	2.82	2.51
[21] RGM		1.39	1.60	2.11	2.87	2.10	3.14
[19] RGM		1.9 (2)	0.6(2)	4(1)	3(1)		
Exp. [2]		1.7±0.3	1.9±0.4				
Exp. [4]		2.4±0.3	5.3±0.4				

Cluster excitations probed by proton and alpha inelastic scattering

Y. Kanada-En'yo with collaborators: K. Ogata, M. Kimura, Y. Chiba, Y. Shikata

Background

Rich cluster phenomena in nuclear excitations

(α,α') is a sensitive probe for cluster states

(p,p') is a good probe for neutron component of excitations in $Z \neq N$ nuclei

reliable reaction analysis is needed to investigate a variety of nuclear excitations from cross sections data

aim

Combination of

- Microscopic reaction approach: g–matrix folding
- Microscopic structure calculation: Antisymmetrized molecular

= cross sections: quantitative, predictive power

- Properties of cluster states, Prediction for new cluster state search
- Neutron and proton contributions in $Z \neq N$ unstable nuclei

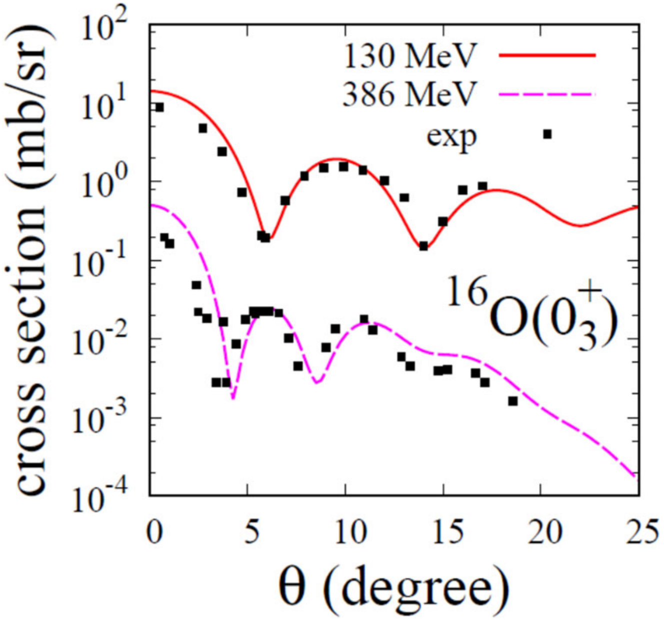
Advantages

No model ambiguity (no adjustable parameters) in reaction part

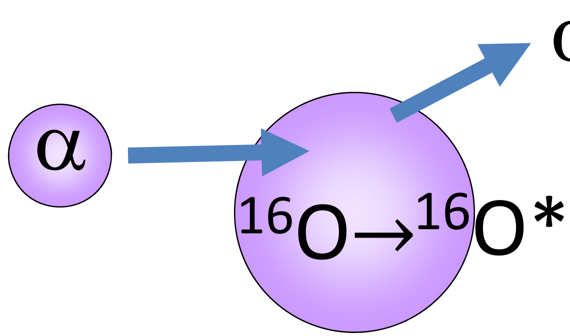
→ Direct connection between structure properties and observables(cross sections)

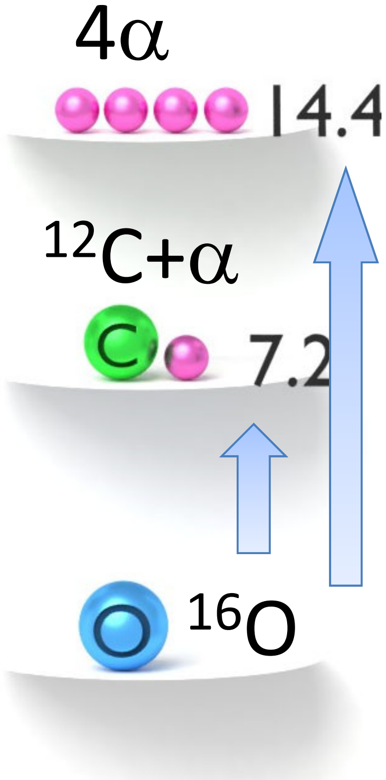
Unified description of different probes: electron, p, α scattering

Result 1 (α,α') for $^{12}C(0^+_3)$ and $^{16}O(0^+_{3,4})$

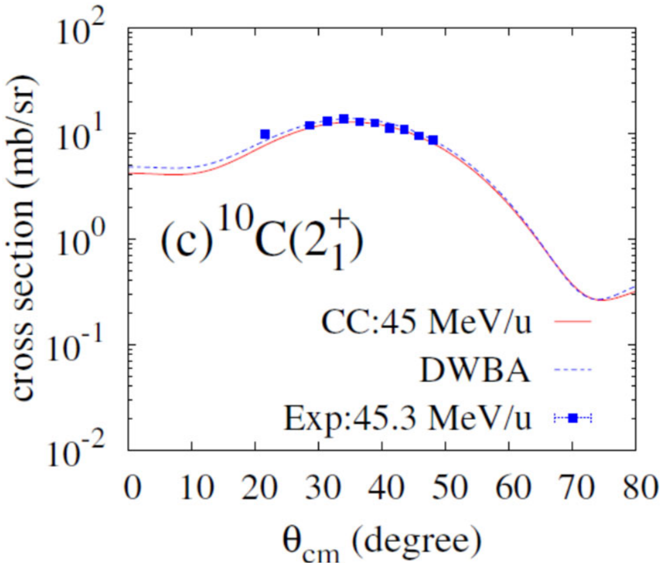


first microscopic calculation !
Successful reproduction



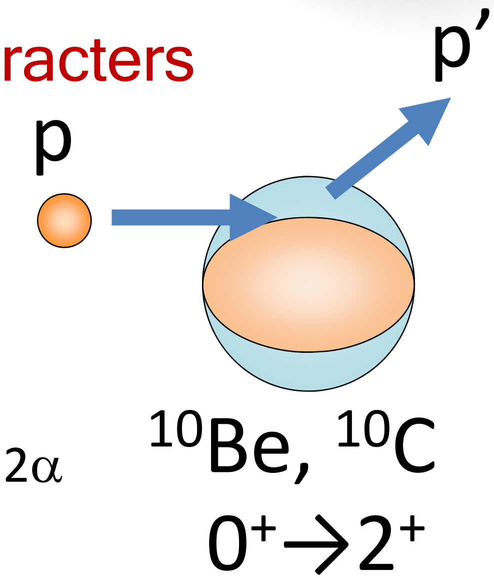


Result 2 (p,p') for $^{10}Be(2^+)$ and $^{16}C(2^+)$:



Different isospin characters

$^{10}Be(2^+_1)$:
isoscalar 2α rotation
$^{10}Be(2^+_2)$:
neutron dominance
excess neutrons around 2α



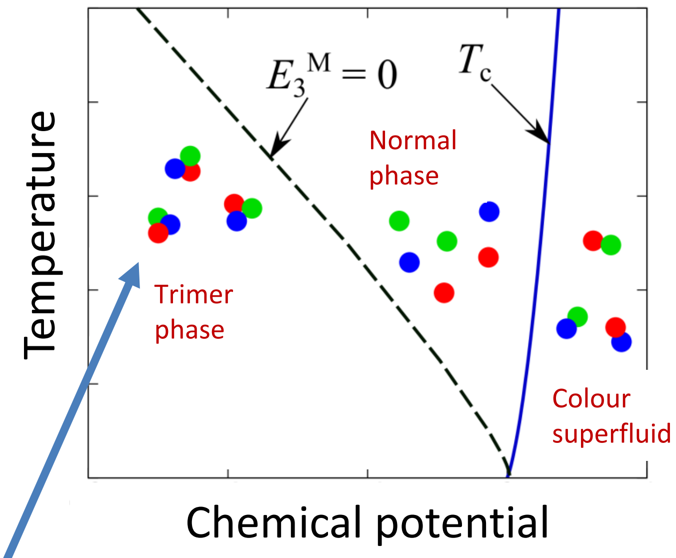
Phase diagram of SU(3) Fermi gases

System made of three kinds of fermions with identical masses and pairwise interactions

→ Efimov effect

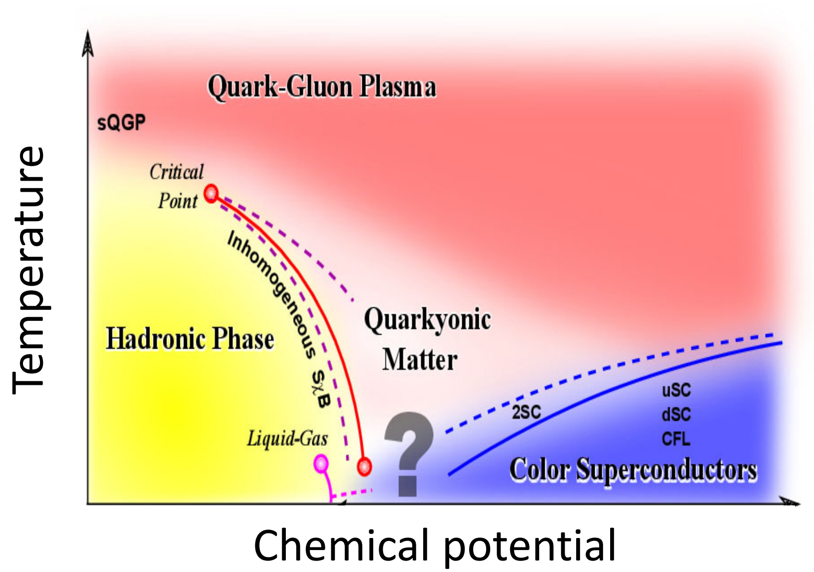
Done by Pascal Naidon

Calculated the phase diagram:

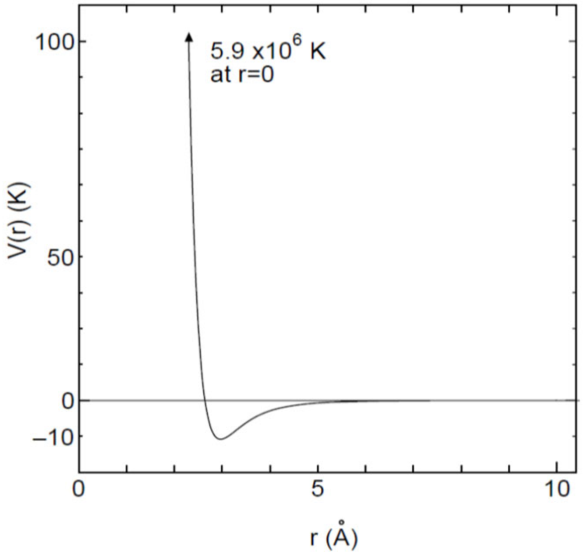


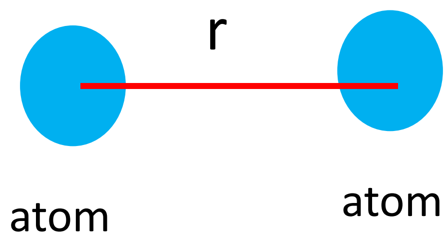
3-body clustering due to the Efimov effect

Analogous to Quark Matter phase diagram:

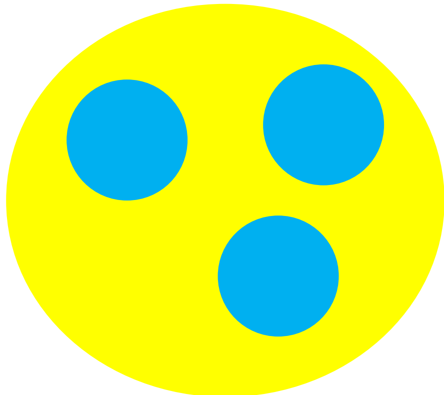


Hiroyuki Tajima, Pascal Naidon, **New Journal of Physics**, 21, 073051 (2019)





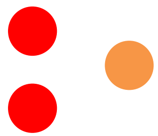
Two-body Potential can de determined by scattering length.
Short range part=>repulsive
Long-distance => attractive



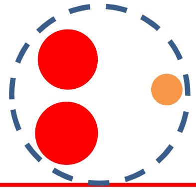
How about 3-body system?
When we apply 2-body potential to 3-body system, two-body potential ambiguity might appear.

Three-body parameter of 2+1 fermions

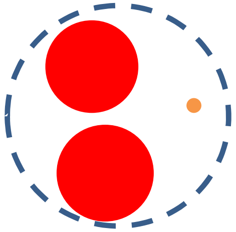
Mixture of two kinds of fermions



Equal masses → No Efimov effect (ex. Spin ½ electrons)
No 3-body clustering



Mass ratio :
8.2 -13.6 → No Efimov effect
Clustering! → Three-body parameter?



Mass ratio > 13.6 → Efimov effect
Clustering → Three-body parameter

Determine the three-body parameter from microscopic interactions between the fermions

Christiane Schmickler, Pascal Naidon, Ludovic Pricoupenko, Emiko Hiyama, **in progress (2020)**

Summary

Key words:

EOS： EOS based on Lattice QCD

Three-body force, baryon-baryon interaction:

construction by LQCD、

three-body force in hypernuclei:ΛN－ΣN couling

Tensor force: contribution of tensor force in neutron-rich nuclei

How to form cluster in neutron-rich nuclei and also

in exotic hadron system.

Di-quark, di-neutron correlation

Universality： ultra cold atomic system, neutron-rich nuclei