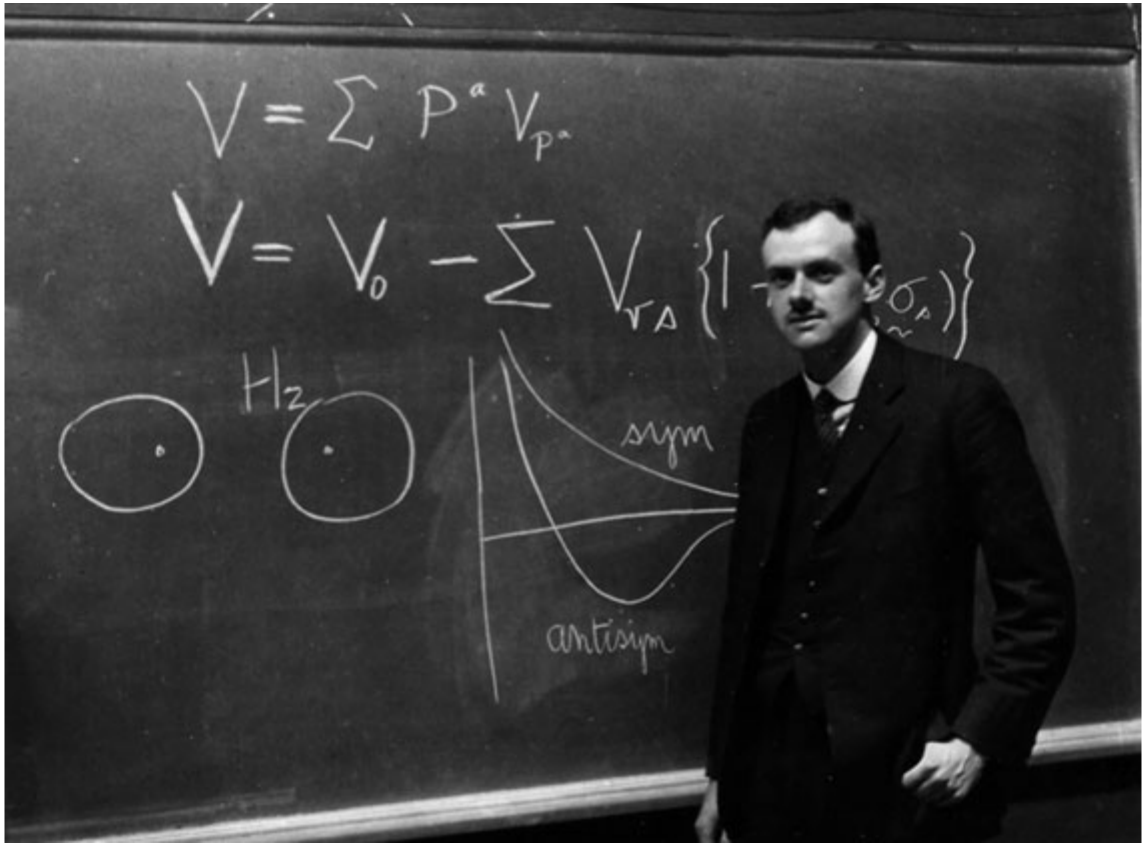
核力研究の歴史と展望



@ 計算科学研究センターワークショップ室

初田哲男 (2013.2.8)

M. G. Mayer’s Nobel Prize Lecture (1963) starts with …


Eugene Paul Wigner


Maria Goeppert Mayer


J. Hans D. Jensen

There are essentially two ways in which physicists at present seek to obtain a consistent picture of atomic nucleus. The first, the basic approach, is to study the elementary particles, their properties and mutual interaction. Thus one hopes to obtain a knowledge of the nuclear forces.

If the forces are known, one should in principle be able to calculate deductively the properties of individual complex nuclei. Only after this has been accomplished can one say that one completely understands nuclear structures.

Considerable progress in this direction has been made in the last few years. The work by Brueckner[1], Bethe[2] and others has developed ways of handling the many-body problem. But our knowledge of the nuclear forces is still far from complete.

The other approach is that of the experimentalist and consists in obtaining by direct experimentation as many data as possible for individual nuclei. One hopes in this way to find regularities and correlations which give a clue to the structure of the nucleus. There are many nuclear models, but I shall speak only of one and leave the others to the next lecture by Professor Jensen.

gene Paul
the
on of
pert Mayer
l structure".

核力研究 (1):

1935年　　中間子論 （湯川秀樹）

1950年-　　三段階論と核力研究 （武谷三男….）

現象論的斥力芯(Jastrow), ω中間子(南部）

Repulsive core : history

Phys. Rev. 81 (1951) 165

On the Nucleon-Nucleon Interaction*

Robert Jastrow**
Institute for Advanced Study, Princeton, New Jersey
(Received August 18, 1950)

A charge-independent interaction between nucleons is assumed, which is characterized by a short range repulsion interior to an attractive well. It is shown that it is then possible to account for the qualitative features of currently known *n-p* and *p-p* scattering data. Some of the implications for saturation are discussed.

Phys. Rev. 106 (1957) 1366

Possible Existence of a Heavy Neutral Meson*

Yoichiro Nambu
The Enrico Fermi Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois
(Received April 25, 1957)

ρ^0 would contribute a repulsive nuclear force of Wigner type and short range ($\lesssim 0.7\times10^{-13}$ cm), more or less similar to the phenomenological hard core.

ω-meson

Most important channels in NN force ($^{2s+1}L_J$)

$$V(\vec{r},\nabla) = V_{\rm C}(r) + S_{12}V_{\rm T}(r) + \vec{\rm L}\cdot\vec{\rm S}\;V_{\rm LS}(r) + \{V_{\rm D}(r),\nabla^2\} + \cdots$$

LO LO NLO NNLO

$^1S_0$ Central force ⟺ nuclear BCS pairing

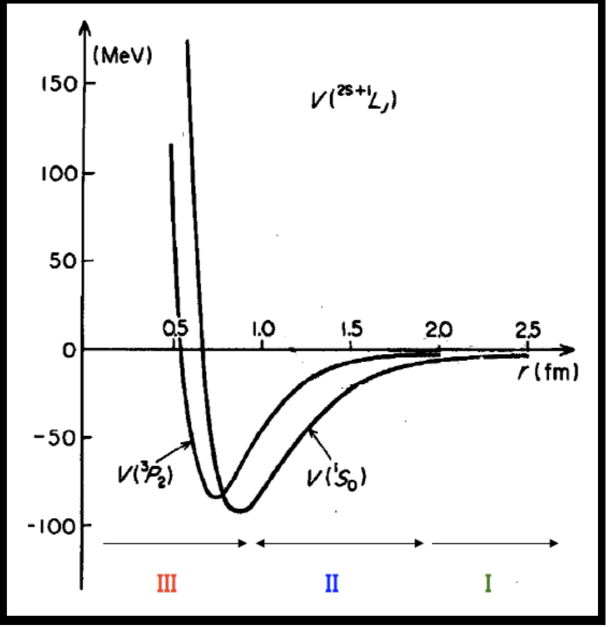
Bohr, Mottelson & Pines, Phys. Rev. 110 (1958)

$^3S_1$-$^3D_1$ Tensor force ⟺ deuteron binding

Schwinger, Phys. Rev. 55 (1939),
Bethe, ibid.57 (1940)
Rarita & Schwinger, ibid. 59 (1941)

$^3P_2$-$^3F_2$ LS force ⟺ neutron superfluidity in neutron stars

Tamagaki, Prog. Theor. Phys. 44 (1970)
Takatsuka-Tamagaki, Prog.Theor. Phys. (1973)



核力研究 (2):

1935年　　中間子論 （湯川秀樹）
1950年-　　三段階論と核力研究 （武谷三男....）
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(大槻-玉垣-安野，町田-並木)
1977年　　クォークによる構造的斥力芯 (Neudachin-Smilnov-玉垣)
1979年　　クォーククラスター模型QCM (岡-矢崎、岡D論)

Structural Core の提唱 (α-α相互作用）

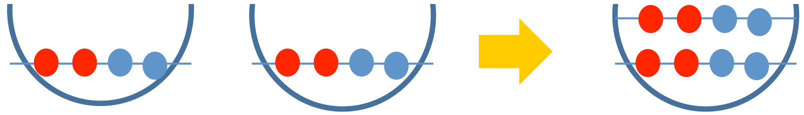
Repulsive Core of Effective α-α Potential

Ryozo TAMAGAKI and Hajime TANAKA

Department of Physics, Hokkaido University
Sapporo

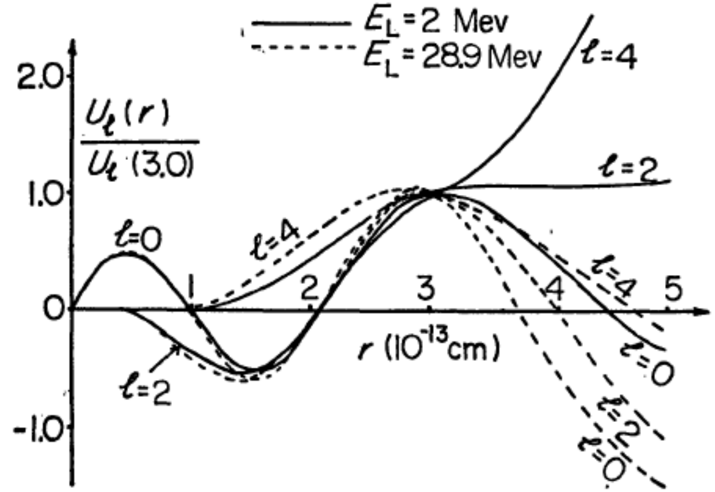
May 10, 1965

Effective α-α potential provides one of the typical examples concerned with interactions acting between particles with a hard internal structure. Recently phenomenological α-α potentials have been well established.[1),2)] The energy-independent but l-dependent potentials reproduce completely the solutions of the phase shift analyses not only in the elastic region ($E_L \lesssim 40$ MeV) but also in the higher energies ($E_L \lesssim 120$ MeV), where l is the α-α relative angular momentum and E_L the laboratory energy.



Resonating Group Method (RGM)
J. Wheeler (Phys. Rev. 52, 1937)

$$\left[-\frac{\hbar^2}{4M}\cdot\frac{d^2}{dr^2}+\frac{\hbar^2 l(l+1)}{4Mr^2}+V_D(r)\right]u_l(r)+\int W_l(r,r')u_l(r')dr'=\frac{\hbar^2k^2}{4M}u_l(r),$$



Structural Core のNN相互作用への応用(ウルバリオン)

Supplement of the Progress of Theoretical Physics, Commemoration Issue for the 30th Anniversary of the Meson Theory by Dr. H. Yukawa, 1965

A Possible Origin of Repulsive Core in Nuclear Forces

Shoichiro OTSUKI, Ryozo TAMAGAKI* and Masaru YASUNO

Department of Physics, Nagoya University, Nagoya

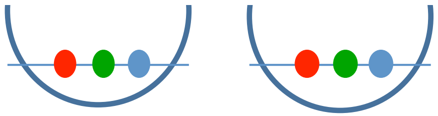
**Department of Physics, Hokkaido University, Sapporo*

(Received June 30, 1965)

A dynamical treatment is made of an originating mechanism of repulsive core provided that the nucleon is a few urfermion system with hard internal structure, by investigating N-N interaction in parallel with α-α one. It is clarified that the originating mechanism of such a "structural" core is closely related, above all, with the internal structure of the composed state of two nucleons (corresponding to Be^8 in the α-α case). A typical exchange kernel expected by the few urfermion structure is proposed, whose effect is almost equivalent to the observed hard core. Some phenomenological aspects of such structural core are discussed.

SU(3) フレーバーへの拡張（町田-並木）

Structural Core のNNへの応用 (色付きクォーク)



Prog. Theor. Phys. Vol. 58 (1977), Sept.

An Explanation of *N*-*N* "Repulsive Core" in Terms of Forbidden States Based on the Quark Model

V. G. NEUDATCHIN, Yu. F. SMIRNOV and Ryozo TAMAGAKI*

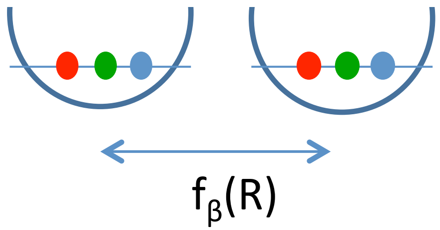
Institute of Nuclear Physics, Moscow State University, Moscow
**Department of Physics, Kyoto University Kyoto 606*

July 5, 1977

Previously a model for the *N*-*N* (nucleon-nucleon) "repulsive core" was proposed from the viewpoint that the Pauli principle among subhadronic constituents of nucleons brings about the almost energy-independent radial node of *N*-*N* wave functions at small distances near "core" radius.[1] Further a

RGMに基づくクォーククラスターモデル

Volume 90B, number 1, 2 PHYSICS LETTERS 11 February 1980



NUCLEAR FORCE IN A QUARK MODEL

M. OKA and K. YAZAKI
Department of Physics, Faculty of Science, University of Tokyo, Bunkyō-ku, Tokyo 113, Japan

Received 24 July 1979

The problem of the nuclear force in a nonrelativistic quark model is studied by the resonating group method which has been extensively used in treating the interaction between composite particles. The calculated phase shifts for the $^3S_1$ and $^1S_0$ states of two nucleons indicate the presence of a strong repulsive force at short distance, while an attractive force is predicted for the $^7S_3((S, T) = (3, 0))$ state of two Δ's. These features are due to an interplay between the Pauli principle and the spin–spin interaction between quarks.

RGM equation

$$\sum_{\beta'} \int [E N_{\beta\beta'}(\boldsymbol{R}, \boldsymbol{R}') - H_{\beta\beta'}(\boldsymbol{R}, \boldsymbol{R}')] f_\beta(\boldsymbol{R}')\, \mathrm{d}\boldsymbol{R}' = 0,$$

核力研究(3):

1935年　中間子論　（湯川秀樹）
1950年-　三段階論と核力研究　（武谷三男....）
現象論的斥力芯(Jastrow), ω中間子(南部）

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(大槻-玉垣-安野、町田-並木)
1977年　クォークによる構造的斥力芯 (Neudachin-Smilnov-玉垣)
1979年　クォーククラスター模型QCM (岡-矢崎、岡D論)

1981年　修士１年入学
1983年　修士論文（核力レビュー＋相対論的QCM）
1985年　Skyrmion間相互作用（藪-安藤, 金田, 齋藤 .....）
1986年　博士論文(Roper共鳴）

核力研究(4):

1935年　　中間子論　（湯川秀樹）
1950年-　　三段階論と核力研究　（武谷三男….）
　　　　　現象論的斥力芯(Jastrow), ω中間子(南部）

1965年　　ウルバリオンによる構造的斥力芯
(大槻-玉垣-安野、町田-並木)
1977年　　クォークによる構造的斥力芯 (Neudachin-Smilnov-玉垣)
1979年　　クォーククラスター模型QCM (岡-矢崎、岡D論)

1981年　　修士１年入学
1983年　　修士論文（核力レビュー＋相対論的QCM）
1985年　　Skyrmion間相互作用（藪-安藤, 金田, 齋藤 .....）
1986年　　博士論文(Roper共鳴）

1986-88　　素粒子現象論@KEK理論部（with　吉村、林）
1988-1993　KEK → Stony Brook → CERN → UW

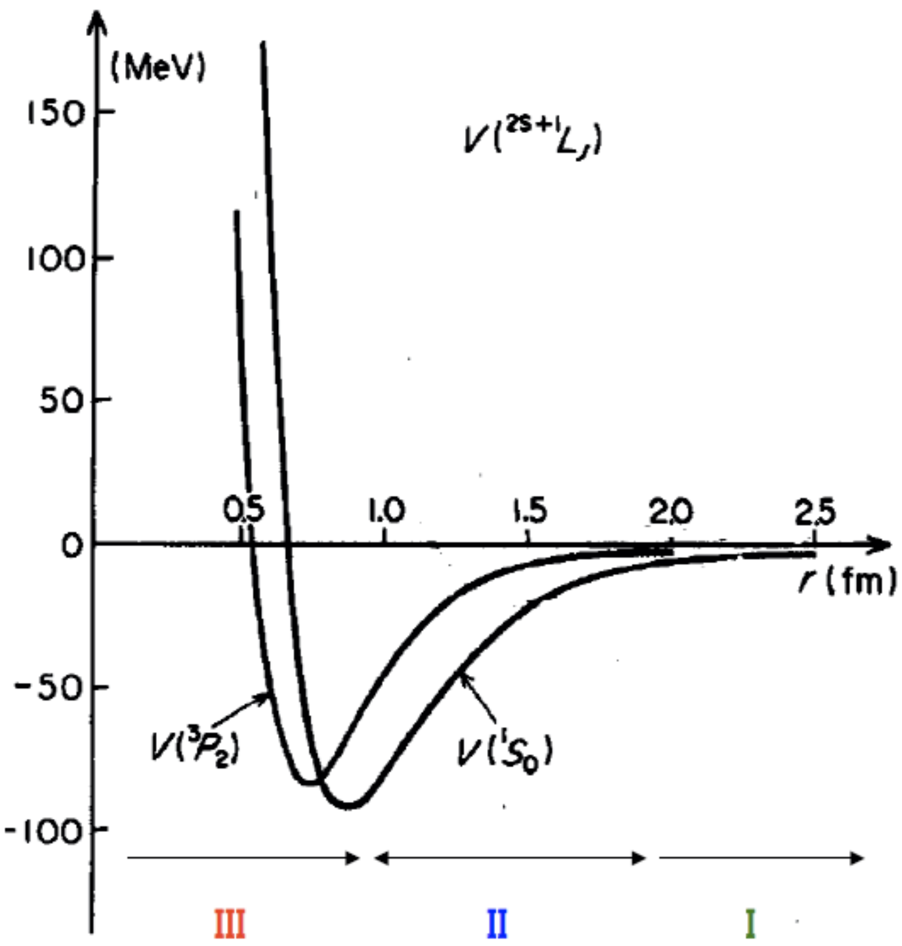
核力研究(5):

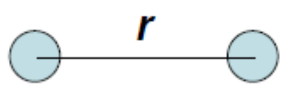
1993年　UW → 筑波大
1994年　宇川さんの格子QCDの個人レッスン
1998-2000　筑波大 → 京大 → 東大

2004年3.29　春の学会＠九大:　山崎さんのππ講演
10.25-27　東大集中講義（青木さん）
2005年2.10　CP-PACS報告会＠筑波: 石塚さんのππ講演
3.02　初田の筑波インフォーマルセミナー

Informal talk @筑波
2005.3.02

Origin of the N-N Repulsive Core
The Most Fundamental Problem in Nuclear Physics





I : OPEP
II : 2π, σ, ω, ρ
III : quark ?

(Taketani)

Informal talk @筑波
2005.3.02

Final answer from lattice QCD ?

1. Short distant N-N potential (r < 1fm) is the most fundamental problem

   whole basis of nuclear and hyper nuclear physics
   whole basis of neutron star physics

2. Origin of the repulsive core

   related to short distance process ?
   channel dependent or universal ?
   hyperon-N and hyperon-hyperon cases ?

3. How to define potential V(r) for composite object such as nucleon

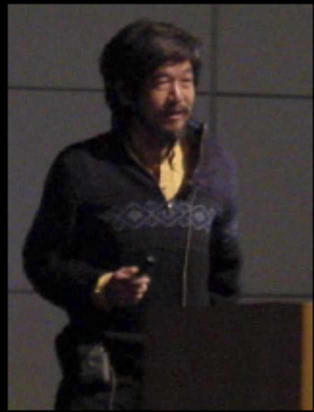
核力研究(6):

1993年　　UW → 筑波大
1994年　　宇川さんの格子QCDの個人レッスン
1998-2000　　筑波大 → 京大 → 東大

2004年3.29　　春の学会@九大:　山崎さんのππ講演
10.25-27　　東大集中講義(青木さん)
2005年2.10　　CP-PACS報告会@筑波:　石塚さんのππ講演
3.02　　初田の筑波インフォーマルセミナー

2005年10月　　石井さん東大着任(特定領域研究研究員)
2006年3 月　　BG/L テスト運用 (大型18 scnfqcd)
4月　　京速シンポ@筑波での初田講演
7月　　Lattice 2006での石井さん講演[arXiv:hep-lat/0610002]

京速シンポ (2006年4月)



4月5日（水曜日）

9:30 － 12:30	セッション3:基礎科学(素粒子，宇宙) 分野

オーガナイザ:梅村 雅之(筑波大学)
講演者・パネリスト:

梅村 雅之　(筑波大学)
introduction

橋本 省二　(KEK)
「次世代の素粒子物理とシミュレーション」

初田 哲男　(東京大学)
「素粒子から原子核・宇宙へ」

青木 慎也　(筑波大学)
「格子QCDで使いやすい計算機は？」

10:30 － 10:45 Break

須佐 元　(立教大学)
「新世代融合型並列計算機と宇宙輻射流体力学」

和田 桂一　(国立天文台)
「天の川創成計画」

牧野 淳一郎　(東京大学)
「GRAPE-DR プロジェクト」

村上 和彰　(九州大学)
「計算機アーキテクトが考える次世代スパコン」

11:40 － 12:30 ディスカッション「基礎科学分野における計算科学の戦略」

核力(斥力芯)の格子計算

第一ステップを準備段階(青木慎也、石井理修、初田哲男):

- クェンチ近似
- 格子間隔:　a=0.1 fm
- 格子サイズ:　48^3 x 80 = $(4.8\ \mathrm{fm})^3$ x 8 fm
- 計算機:　Blue Gene/L
- 2核子のBS振幅 → 核力

将来:

- 状態(スピン・アイソスピン・角運動量)依存性
- ハイペロン間力　<–> J-PARC
- フルQCD
- 3体核力

物質安定性の根本理由が解明される
QCDによる核物理の基礎が構築される
湯川秀樹に初まる核力研究の最高到達点となる

格子QCDによる
核力計算結果
の初公開
（Lattice2006)

Nuclear Force from Lattice QCD

Noriyoshi ISHII*
Department of Physics, University of Tokyo, Tokyo 113–0033, JAPAN
E-mail: ishii@rarfaxp.riken.jp

Sinya AOKI
Graduate School of Pure and Applied Science, University of Tsukuba, Tukuba 305–8571, Ibaraki, JAPAN
E-mail: saoki@het.ph.tsukuba.ac.jp

Tetsuo HATSUDA
Department of Physics, University of Tokyo, Tokyo 113–0033, JAPAN
E-mail: hatsuda@phys.s.u-tokyo.ac.jp

The first lattice QCD result on the nuclear force (the
level. The standard Wilson gauge action and the st
on the lattice of the size $16^3 \times 24$ with the gauge co
$\kappa = 0.1665$. To obtain the NN potential, we adopt
collaboration to study the $\pi\pi$ scattering phase shift.
NN potentials which are faithful to those obtained
identifying the equal-time Bethe-Salpeter wave funct
the two nucleon system, the NN potential is reconstr
time-independent Schrödinger equation. In this repo
$I = 1$ channel, which enables us to pick up unambigu
The resulting potential is seen to posses a clear repuls
($r \lesssim 0.5$ fm). Although the attraction in the intermedi
in the present lattice set-up, our method is appeared
NN potential with lattice QCD.

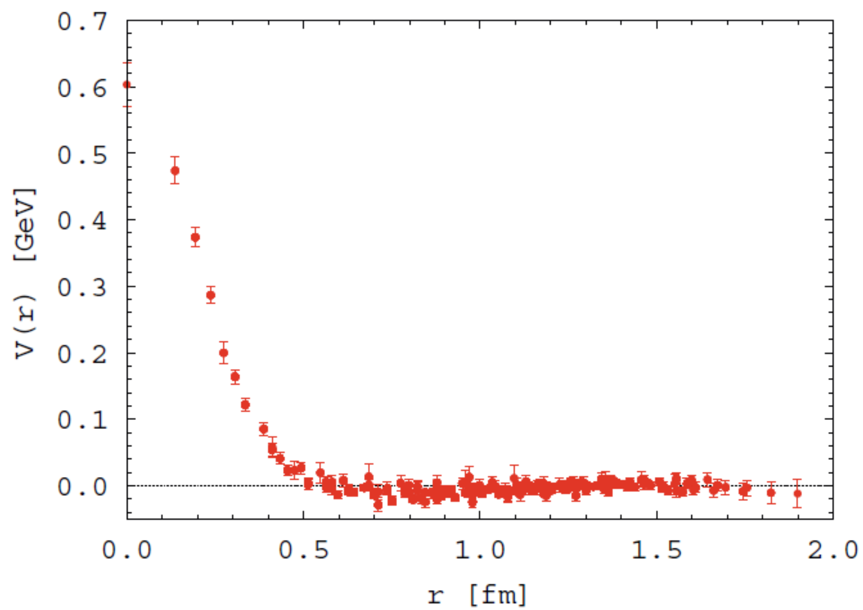


Figure 3: The lattice QCD result of the NN potential $V_{\mathrm{central}}(r)$.

核力研究(7):

1993年　UW → 筑波大
1994年　宇川さんの格子QCDの個人レッスン
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2006年11.28　PRL submitted [nucl-th/0611096]
12月　e-mail from Frank Wilczek saying “Great!”
2007年1.25　Wilczek 講演@湯川朝永
7.12　PRL accepted

PRL **99,** 022001 (2007) PHYSICAL REVIEW LETTERS week ending 13 JULY 2007

Nuclear Force from Lattice QCD

N. Ishii,[1,2] S. Aoki,[3,4] and T. Hatsuda[2]

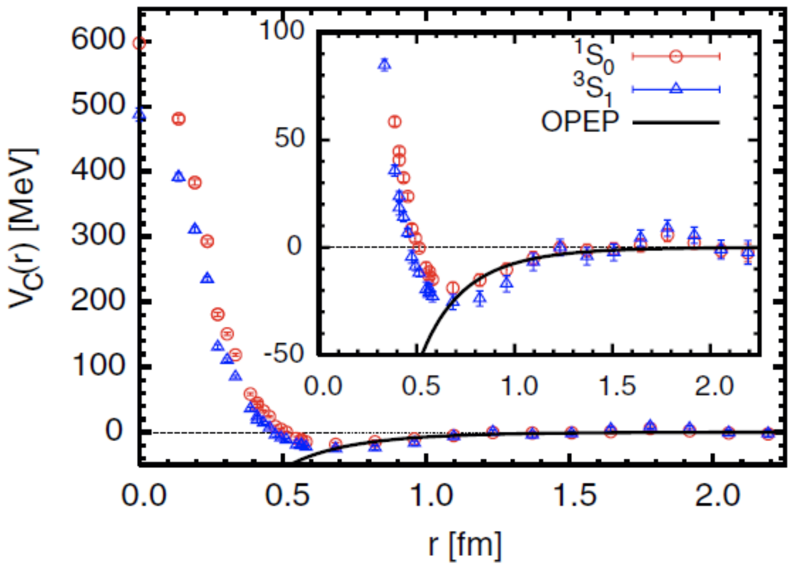
[1]*Center for Computational Sciences, University of Tsukuba, Tsukuba 305-8577, Ibaraki, Japan*
[2]*Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*
[3]*Graduate School of Pure and Applied Sciences, University of Tsukuba, Tsukuba 305-8571, Ibaraki, Japan*
[4]*RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA*

(Received 28 November 2006; published 12 July 2007)

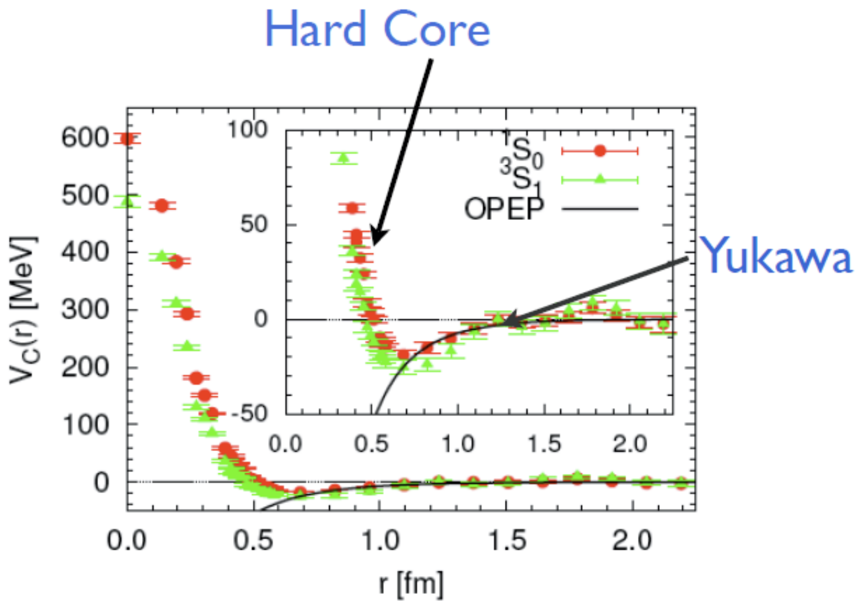
The nucleon-nucleon (NN) potential is studied by lattice QCD simulations in the quenched approximation, using the plaquette gauge action and the Wilson quark action on a 32^4 [$\simeq(4.4\text{ fm})^4$] lattice. A NN potential $V_{NN}(r)$ is defined from the equal-time Bethe-Salpeter amplitude with a local interpolating operator for the nucleon. By studying the NN interaction in the ${}^1S_0$ and ${}^3S_1$ channels, we show that the central part of $V_{NN}(r)$ has a strong repulsive core of a few hundred MeV at short distances ($r \lesssim 0.5$ fm) surrounded by an attractive well at medium and long distances. These features are consistent with the known phenomenological features of the nuclear force.

格子QCDによる核力の初論文
-- 産みの苦しみ --

$$-\frac{1}{2\mu}\nabla^2\phi(\vec{r}) + \int d^3r' U(\vec{r},\vec{r}')\phi(\vec{r}') = E\phi(\vec{r}),$$



Frank Wilczek：
湯川朝永生誕百年記念講演
(京都大学、1月 23日, 2007)



At still shorter distances, however, many more mesons become relevant. Also at these short distances their internal structure is resolved, so it is not valid to treat them as the irreducible units, or quanta. The real quanta are quarks and gluons. We can't fall back on Yukawa's theory any more; we can't avoid working the quarks and gluons.

On the experimental side, we find that at short distances the nuclear force becomes strongly repulsive. This is the famous "hard core" of nuclear physics. Without the "hard core" repulsion, atomic nuclei would collapse.

Just in the last few weeks, Ishii, Aoki, and Hatsuda reported the first calculation of the nuclear force based on QCD. They do find the hard core. It is a major milestone in our fundamental understanding of matter.

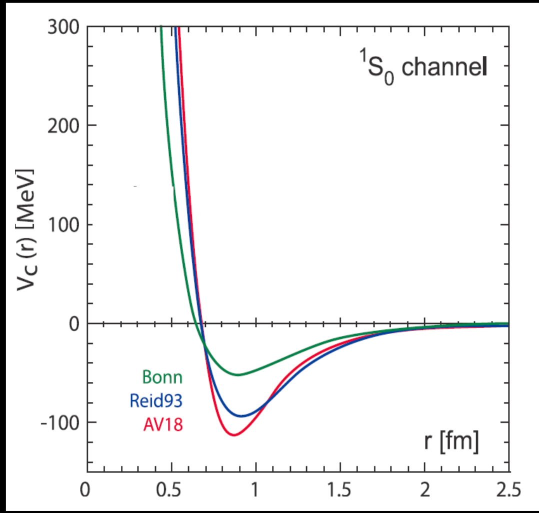
http://tkynt2.phys.s.u-tokyo.ac.jp/~hatsuda/Wilczek_talk.pdf

phenomenological nuclear forces

- NN int.: about 4500 np and pp scatt. data

“high precision” NN interactions	# of parameters
CD Bonn (p space)	38
AV18 (r space)	40
EFT in N^3LO ($n\pi$+contact)	24

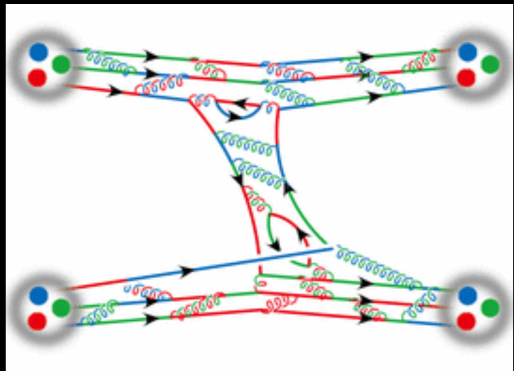
R. Machleidt, arXiv:0704.0807 [nucl-th]

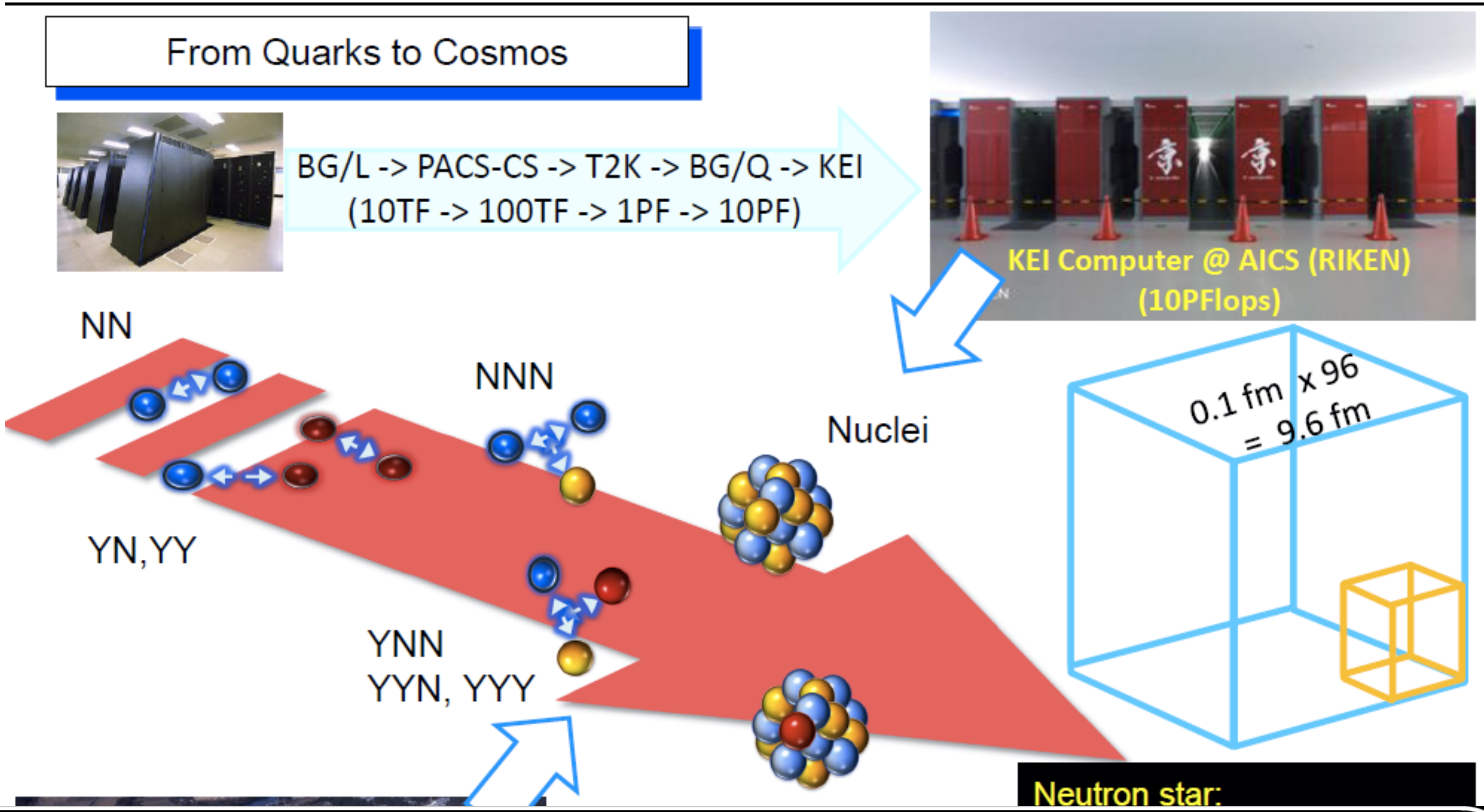


- NNN, YN, YY : data very limited
- YYN, YNN, YYY : none

QCD has only four parameters :

m_u, m_d, m_s, Λ_{QCD}





Hadrons to Atomic nuclei
HAL
from Lattice QCD

Univ. Tsukuba	S. Aoki, N. Ishii, H. Nemura, F. Etminan, M. Yamada, K. Sasaki
RIKEN	K. Murano, T. Doi, Y. Ikeda, T. Hatsuda
Nihon Univ.	T. Inoue
Univ. Tokyo	B. Charron

Nuclear Structure （Bohr-Mottelson, 3rd edition, 2020)

Chapter 1 Basic properties of atomic nuclei

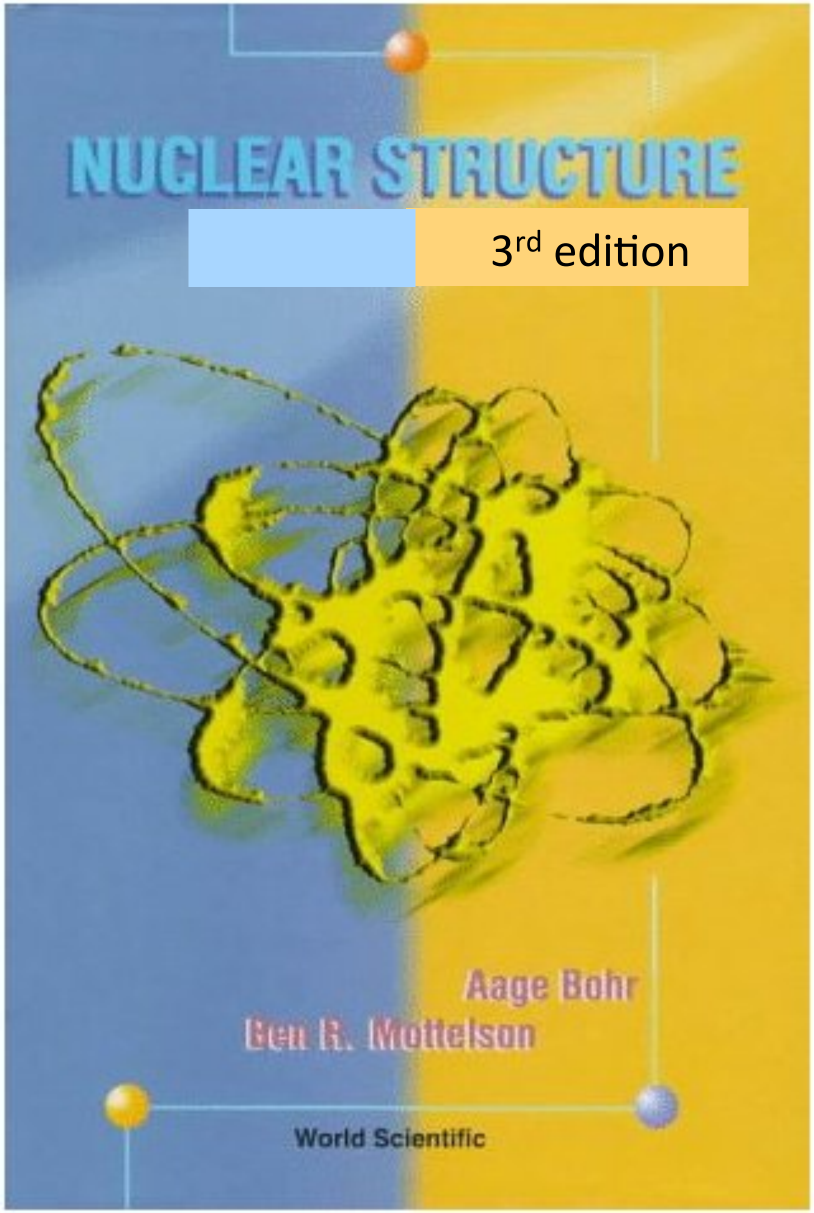
Chapter 2 Nuclear force
- 2-1. Quantum Chromodynamics
- 2-2. Nuclear force from QCD
- 2-3. BB and BBB forces from QCD

Chapter 3 Nuclear structure
- 3-1 Nuclear models
- 3-2 Quantum many-body theories
- 3-4 Ab initio techniques
- 3-5 Density functional theory

Chapter 4 Nuclear astrophysics

Chapter 5 Applications of nuclear physics

Appendix



Backup slides

Progress of Theoretical Physics, Vol. 66, No. 2, August 1981

Short Range Part of Baryon-Baryon Interaction in a Quark Model. I

— Formulation —

Makoto OKA*) and Koichi YAZAKI

Department of Physics, University of Tokyo, Tokyo 113

(Received December 19, 1980)

The short range part of the interaction between non-strange baryons (N and Δ) is studied in a nonrelativistic quark model. The mass of a quark is assumed to be about one-third of the nucleon mass and the quark-quark interaction consists of a confinement term and the one gluon exchange potential. Baryons are described as clusters of three quarks and the resonating group method, which has been extensively developed in the nuclear cluster model, is used to treat the bound state and scattering problems of two baryons. This paper discusses the formal aspects of the present approach, while the numerical results will be given in the subsequent paper.

RGM equation

$$\int [H(\boldsymbol{R},\boldsymbol{R}') - EN(\boldsymbol{R},\boldsymbol{R}')]\chi(\boldsymbol{R}')d\boldsymbol{R}' = 0$$

$$\chi_R(\boldsymbol{R}) \equiv \int N^{1/2}(\boldsymbol{R},\boldsymbol{R}')\chi(\boldsymbol{R}')d\boldsymbol{R}',$$

⇨

non-local Schrödinger type equation:

$$\int \mathcal{H}(\boldsymbol{R},\boldsymbol{R}')\chi_R(\boldsymbol{R}')d\boldsymbol{R}' = E\chi_R(\boldsymbol{R}),$$

Progress of Theoretical Physics, Vol. 66, No. 2, August 1981

Short Range Part of Baryon-Baryon Interaction in a Quark Model. II

— Numerical Results for S-Wave —

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Institute for Nuclear Study, University of Tokyo
Tanashi, Tokyo 188
**Department of Physics, University of Tokyo, Tokyo 113*

(Received January 24, 1981)

An approach to the short
tic quark model, proposed and
relative motion. Repulsive c
states, including the NN syste
predicted for the $\Delta\Delta$ system
the Pauli principle between c
insensitive to the confinement
the present non-relativistic qu
local potential. Qualitative b
way.

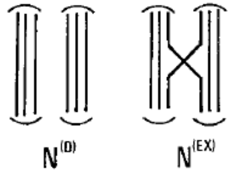


Fig. 1. The normalization kernel.

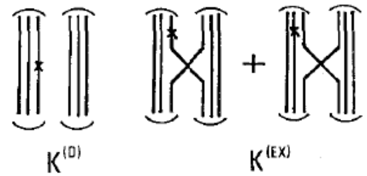


Fig. 2. The kinetic energy kernel. The symbol × denotes the kinetic energy insertion.

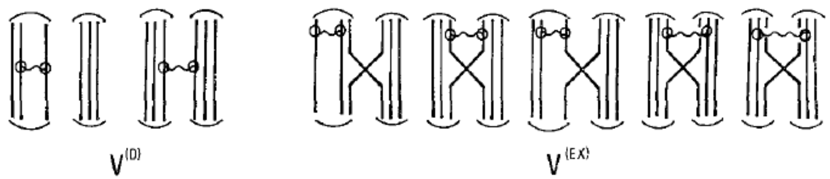


Fig. 3. The direct (a) and the exchage (b) parts of the interaction kernel. The wavy line denotes the two-body potential.

東大グループ(清水、森松、竹内、小池、…), 土岐、藤原, 鈴木、Hecht, Faessler, ……

Skyrmionによる核力

Progress of Theoretical Physics, Vol. 74, No. 4, October 1985

Static N-N and N-$\bar{N}$ Interactions in the Skyrme Model

Hiroyuki YABU and Kazuhiko ANDŌ

Department of Physics, Kyoto University, Kyoto 606

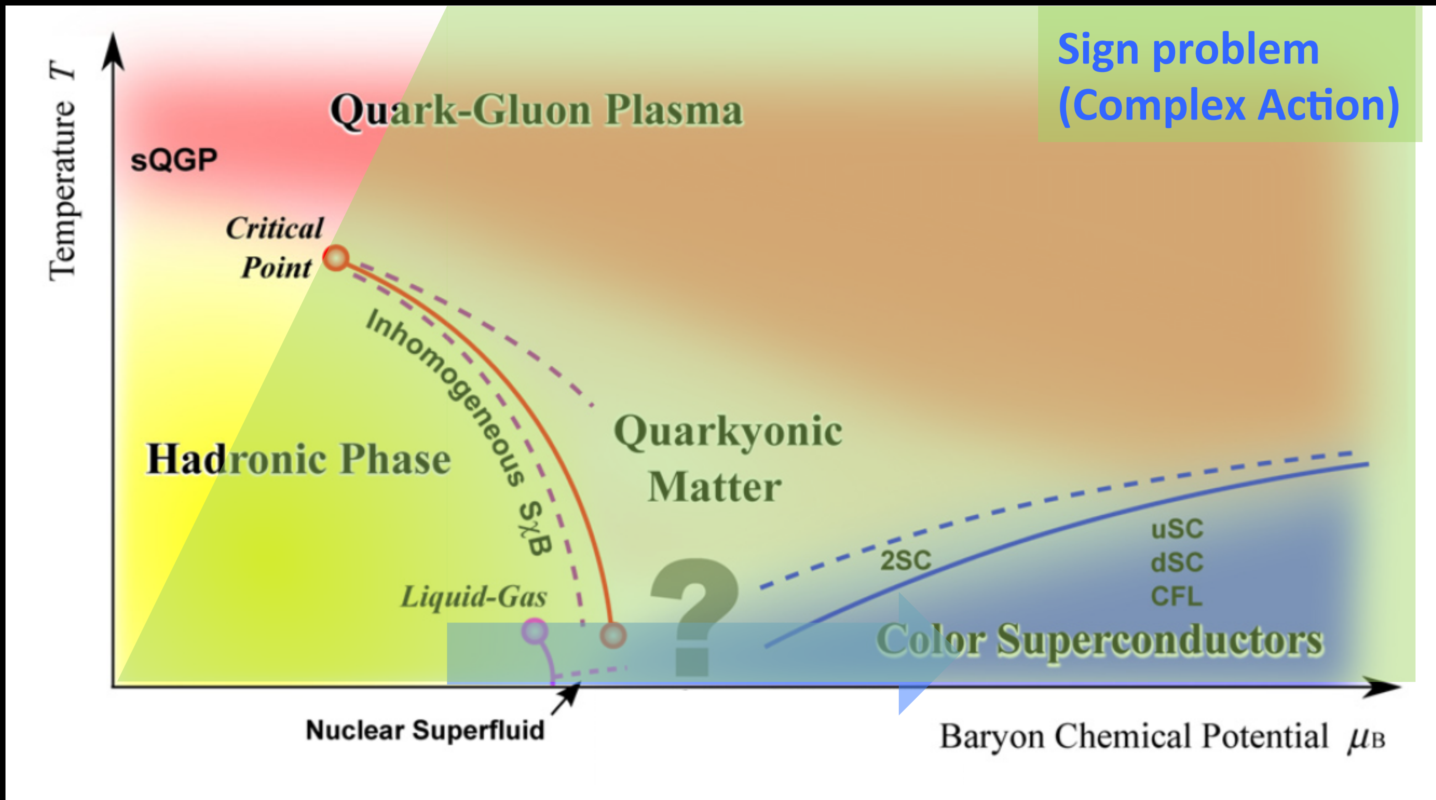
(Received May 27, 1985)

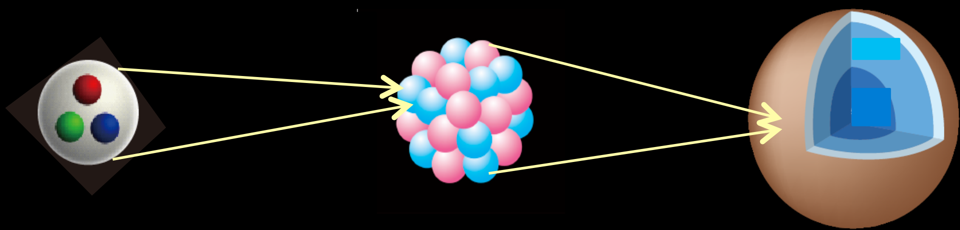
Static nucleon-nucleon (N-N) and nucleon-antinucleon (N-$\bar{N}$) interactions in the Skyrme model are calculated using the so-called product approximation. Properties of the obtained interactions are examined and discussed in terms of the G-parity transformation based on the meson exchange picture. It is shown that the state-independent repulsive term found in the N-N potential remains completely unchanged in the N-$\bar{N}$ case, which is at variance with the ω-meson exchange effect. In long and intermediate range parts of the isovector spin-spin and tensor interaction, one pion and ρ-meson like effects are clearly exhibited. A feature possibly attributable to the A_1-meson is also noticed.

$$V^{BB}(\boldsymbol{s};\, e_{ai}(1),\, e_{bj}(2)) = -\int \mathcal{L}[U_{BB}(\boldsymbol{x})]d^3x - 2M_S\,,$$

名大-新潟大グループ(斎藤、乙藤、金田、...), Jackson, Rho, ..., 橋本(幸士),

QCD Phase diagram

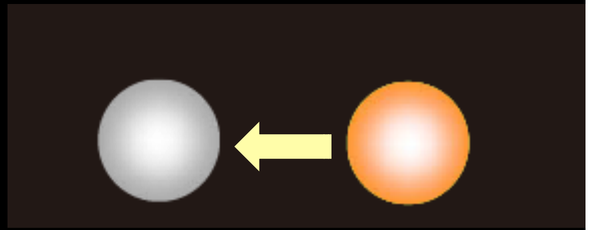


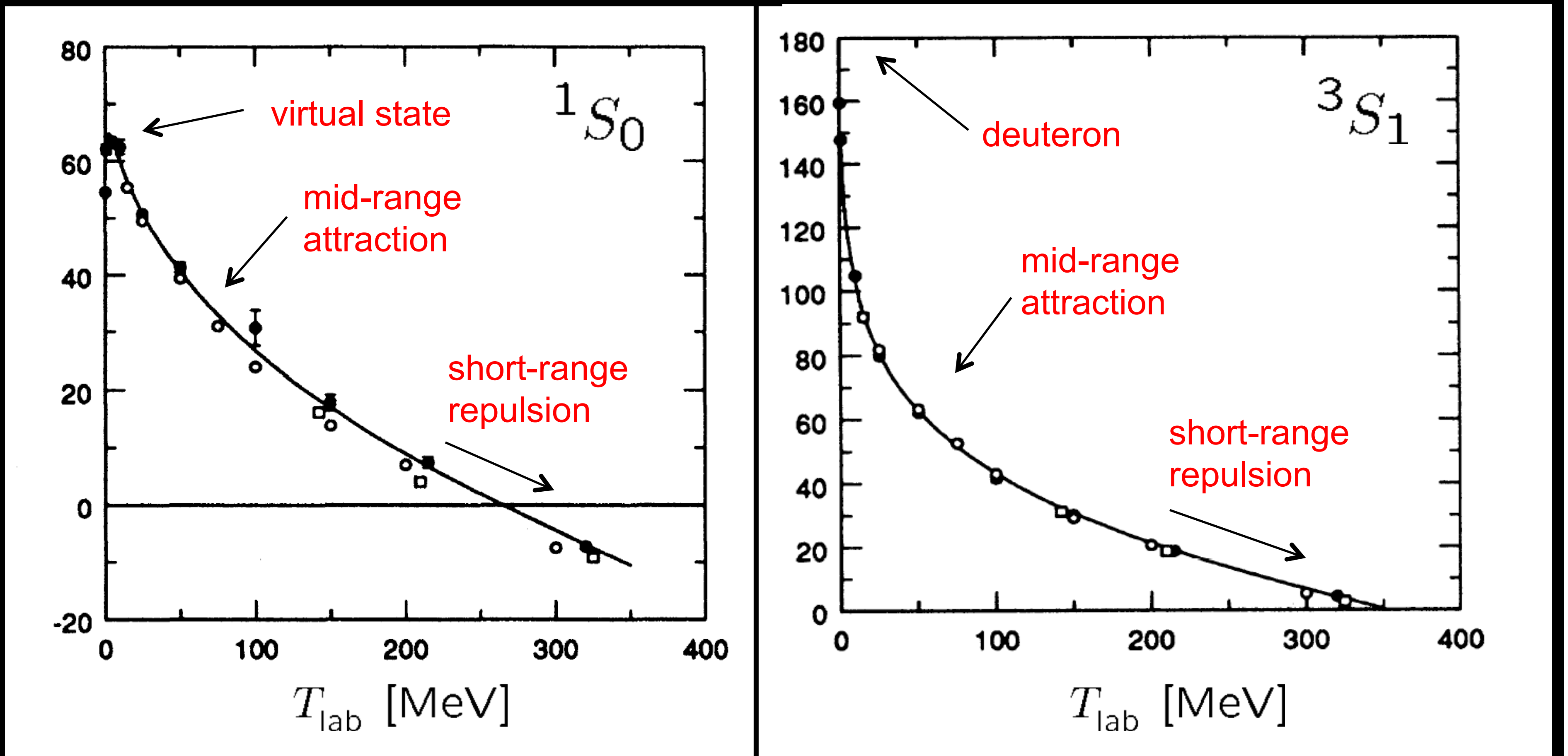


K. Fukushima and T. Hatsuda,
Rep. Prog. Phys. 74 (2011) 014001

NN interactions
critical inputs in nuclear physics

$^{2S+1}L_J$





Nijmegen partial-wave analysis,
Stoks et al., Phys.Rev. C48 (1993) 792

2011.11.10

玉垣先生

（前略）

思い返せば、大学院に入ったころから玉垣先生には 核力の重要性、特にその
クォークレベルからの理解の 重要性を教えて頂き、修士論文での最終目標も
相対論的なクォーク模型に基づいた核力の理解という ことでした
（当時はそこまで到達せず、単体のバリオンの話で 終わってしまいましたが。）

（中略）

いまでも、玉垣先生の書かれた核力と核物質のレビュー や大学院での核力と
核物質に関する講義ノートを 手元に、指針とさせて 頂いております。古くて新しい
核力のミクロな理解に だんだん近づいてきたという感じを強く持っています。

（後略）

初田哲男

初田哲男様

2011.11.12

基礎的相互作用から核力を研究する本流で、世界で先鞭をきった画期的研究ですから価値は高いです。いずれ教科書にも書かれる業績でしょう。

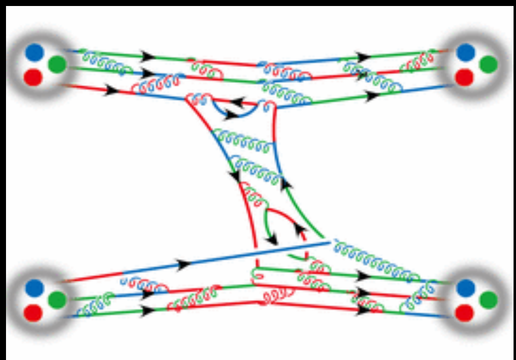
(中略）

優れた研究をするには、個人の能力は勿論大事ですが、良い方針＋それを具体化する契機をつかむこと、よい共同研究者に恵まれること が大切です。

(後略）

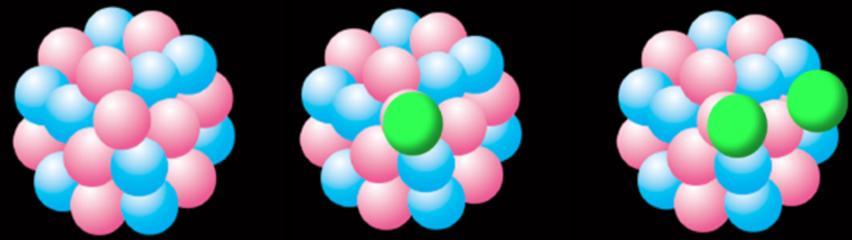
玉垣良三

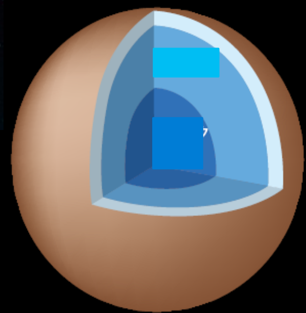
From LQCD
to Nuclear & Astro physics
-- bottom-up approach --



Lattice QCD

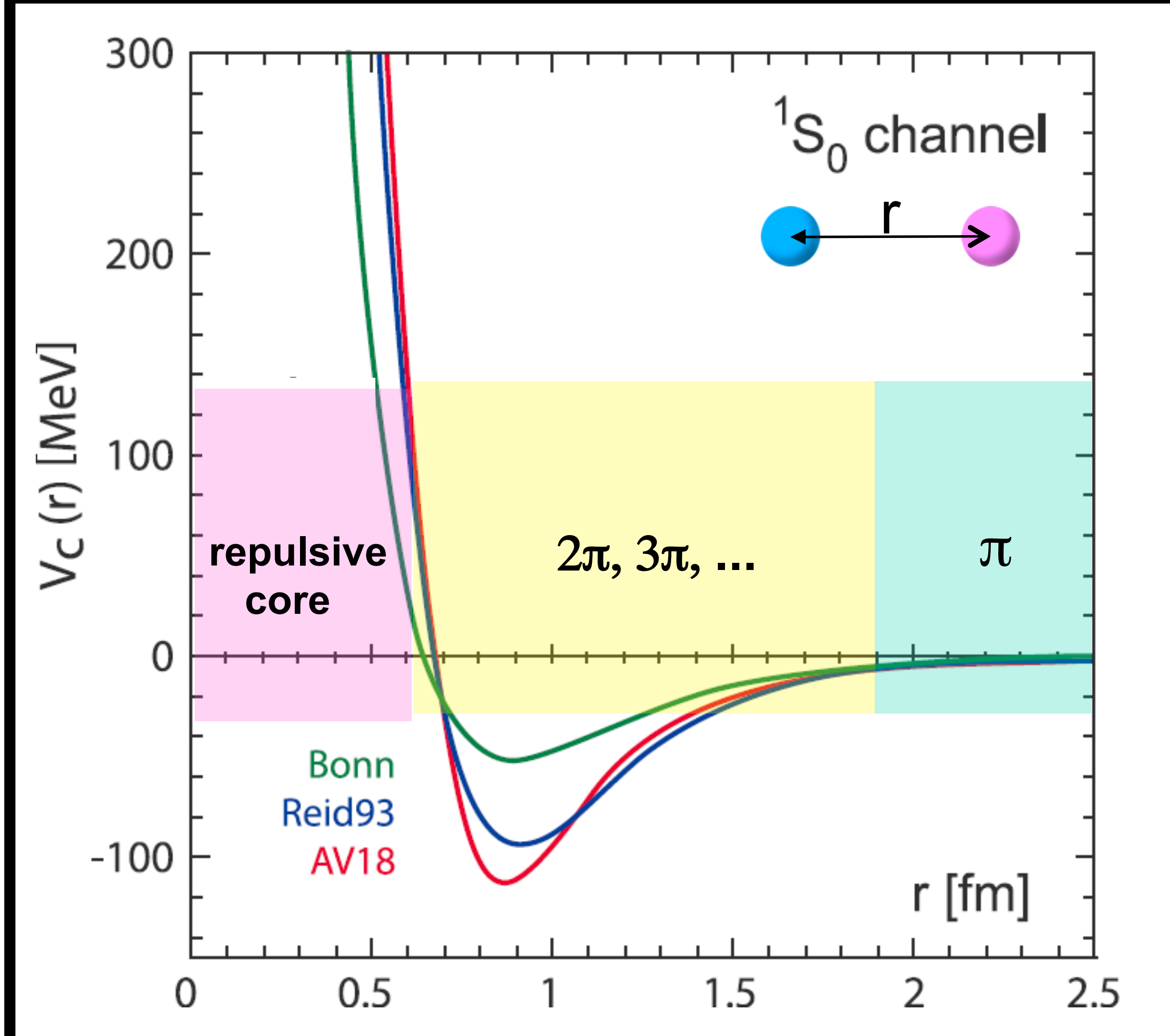
・Nuclear
many-body
methods
・Supernova
simulation





新学術「素核宇宙融合」 (2008-2012)
HPCI 戦略分野5「物質と宇宙の起源と構造」(2010-2015)

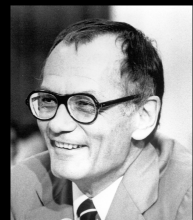
Nuclear force: a brief history



- One-pion exchange
  Yukawa (1935)

- Multi-pion
  Taketani et al. (1951)

- Repulsive core
  Jastrow (1951) Nambu (1957)



- EFT
  Weinberg (1990)

high precision NN force (90's-)
30-40 parameters
5000 phase shift data