Dibaryons in Hadronic and Nuclear Physics: New Theoretical and Experimental Results

В.И. Кукулин,
М.Н. Платонова, В.Н. Померанцев

Семинар по ядерной физике
НИИЯФ МГУ
10 ноября 2015 г.

Nuclear Force:
early stage

Physics Today **7**(2), 5 (1954)

Mesons and Nuclear Forces

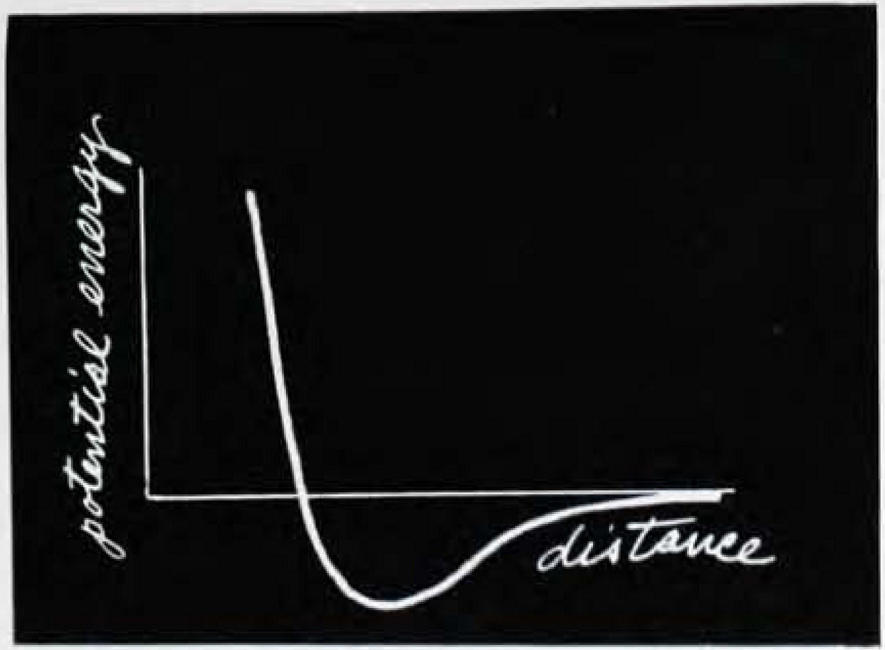
The text of the twenty-second Joseph Henry Lecture delivered before the Philosophical Society of Washington April 24, 1953

By Hans A. Bethe

Hans A. Bethe is professor of physics at Cornell University. Born and educated in Germany, Professor Bethe received his PhD at Munich in 1928 and taught physics at Frankfurt, Stuttgart, Munich, and Tuebingen before leaving Germany in 1933 to go to Manchester University in England. In 1935 he came to the United States as associate professor at Cornell. In 1942–43 he was a staff member of the MIT Radiation Laboratory, and from 1943 until the end of the war he headed the theoretical physics division at Los Alamos.

THE HISTORY of the subject of mesons and nuclear forces is an example, as good as any I know in recent scientific progress, of both the wisdom and the folly of scientists. The theory of nuclear forces began in 1932 with the discovery of the neutron. This made possible a consistent picture of the structure of the nucleus, namely, to consider the nucleus as composed of neutrons and protons which are held together by very strong forces, different from and stronger than any other forces which we had known in nature before. Only three years after the discovery of the neutron and the start of nuclear theory, Yukawa suggested that the nuclear forces were transmitted between the nuclear particles, the neutron and the proton, by other particles as yet undiscovered, which have now come to be known by the name of mesons. Yukawa predicted that there should be such particles, that they should have a mass of 100 to 200 times the electron mass, that they should be charged, and that they should have integral spin, probably either zero or one.

Three years later, Yukawa's prediction came true. Particles were discovered in cosmic radiation by two groups of people, Anderson and Neddermeyer, working at the California Institute of Technology, and Street and Stevenson, working at Harvard University. These particles had a mass of about 200 electron masses, they had a positive or a negative charge just as Yukawa had wanted, and they seemed to fulfill pretty well his program. In the succeeding nine years experimental physicists kept discovering more and more properties of these particles and theoretical physicists kept calculating what such particles would do for nuclear forces.



pulsion stops. The most this can do is to give a phase shift proportional to the radius of the repulsive region, and this phase shift will be completely independent of the *magnitude* of the repulsive potential. So Drell and Henley showed not only that the weak coupling theory was wrong all along, but also *why* it was wrong and what should be done instead.

The next major progress was made by Chew, of the University of Illinois, who did the same for the attraction that Drell and Henley had done for the repulsion; namely, he showed how one could calculate, at least in principle, the effects of the attractive force in a sensible way without using perturbation theory. He was able to

Conclusion

I think that one can say at present that although the pseudoscalar meson theory is not yet able to explain quantitatively the meson-nucleon scattering, there is no cause for disbelieving it, because there is no qualitative discrepancy between the predictions of the theory and the experiments. It is likely to be just a matter of learning how to treat strong interactions before we can get quantitative results on meson scattering.

The question of nuclear forces, as I said, is much more complicated. Lévy's first attempt was extremely valuable because it showed that in principle the theory gave the right behavior of nuclear forces. In detail, numerous theoretical physicists have criticized Lévy's paper, and this is not surprising. However, the theory can explain why nuclei hold together, why you have strong forces, and why nucleons do not completely fall into each other. It predicts the interesting phenomenon of many-body forces; that is, it predicts that you have interactions not only between two nucleons, but also between three or more nucleons which hand a meson to each other around the circle. Weisskopf and his collaborators have pointed out that these many-body forces may be quite important for the explanation of the phenomenon of saturation of nuclear forces, that is, for the phenomenon that heavy nuclei also do not collapse. We can deduce from the pseudoscalar theory that nuclear forces depend on spin and deduce that there is a quadrupole moment of the deuteron.

While the Yukawa mechanism gave a correct picture for the long-range nuclear force through a π-meson exchange, the nature of the short-range NN repulsion remained obscure.

So, we addressed the very old and still not well understood and intriguing question:

What is the machinery behind short-range nuclear force and short-range correlations in nuclei?

Or, in other words:

What is the nature of short-range nuclear force, i.e. whether it is of meson-exchange origin, or quark-string dynamics, or … ?

This fundamental question can be formulated in other form:

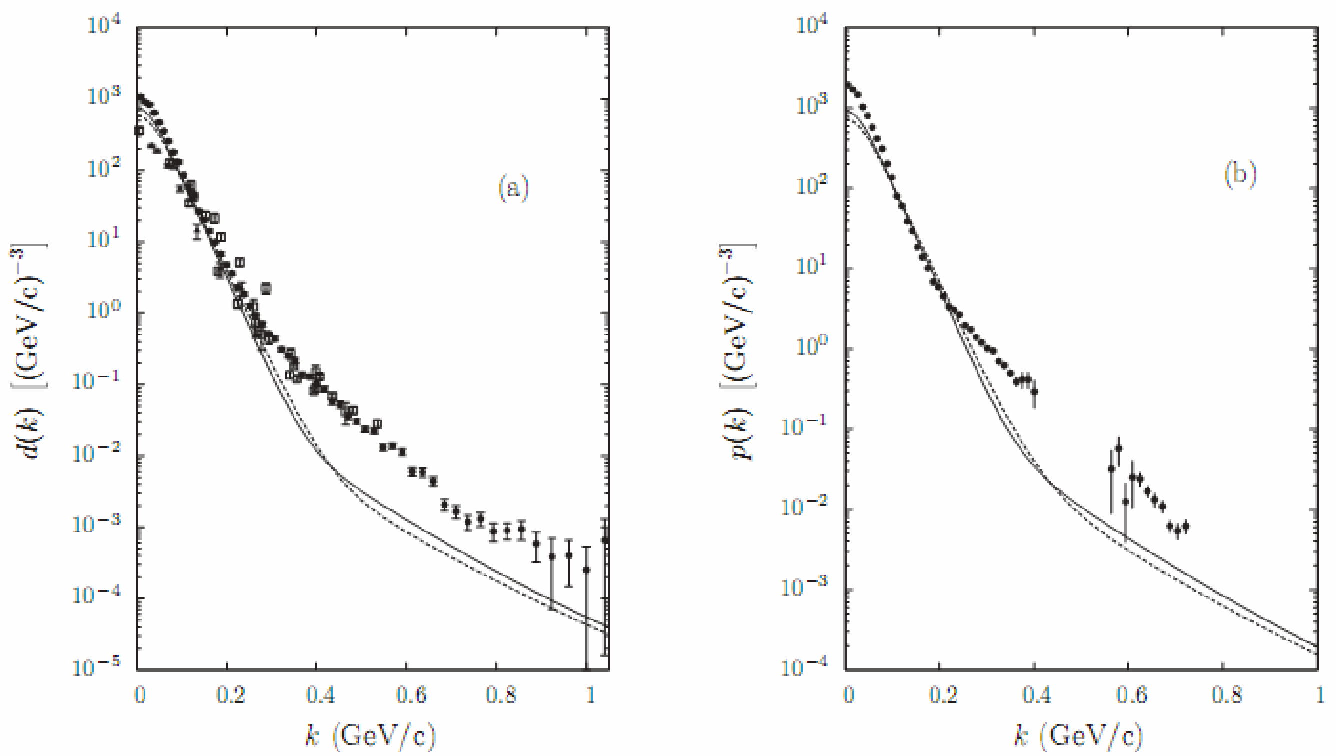
What is the origin and nature of high-momentum components in nuclear wave functions?

As is well known there is a significant surplus of high momentum components in nuclear wave functions observed in many experiments with high-energy probes as compared to the theoretical predictions based on modern realistic 2N and 3N forces.

This actually means that the existing short-range repulsive core in NN force is not sufficient to predict so large abundance of short-range correlations.

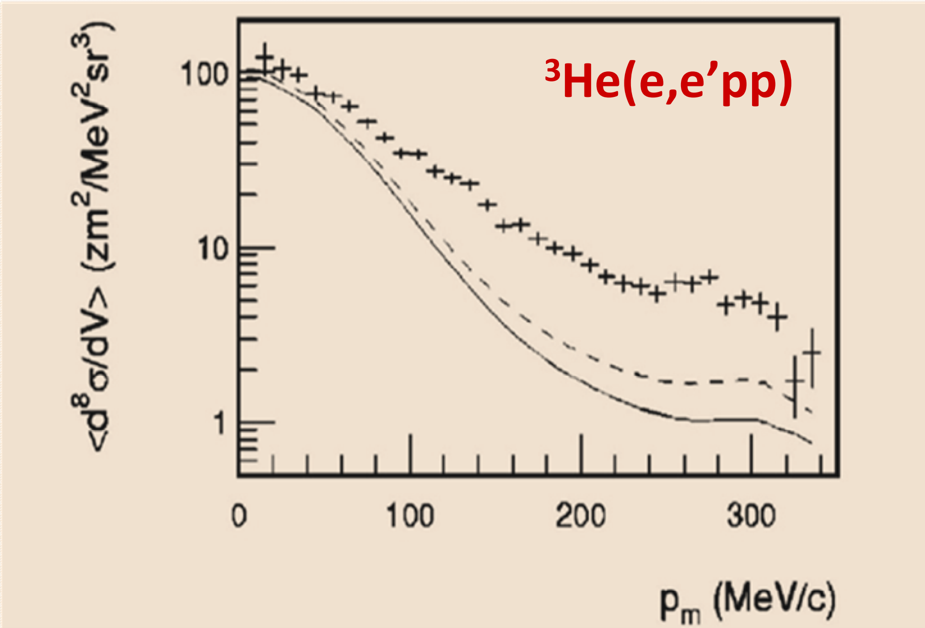
Some examples

- Numerous experiments demonstrate very clearly the high-momentum correlations of nucleons in all nuclei with momenta p_m > 200 – 300 MeV/*c*, i.e., *well beyond the maximum Fermi-motion nucleon momentum in nuclei.*
- The reliable source for such high-momentum correlations is not fully evident for today.

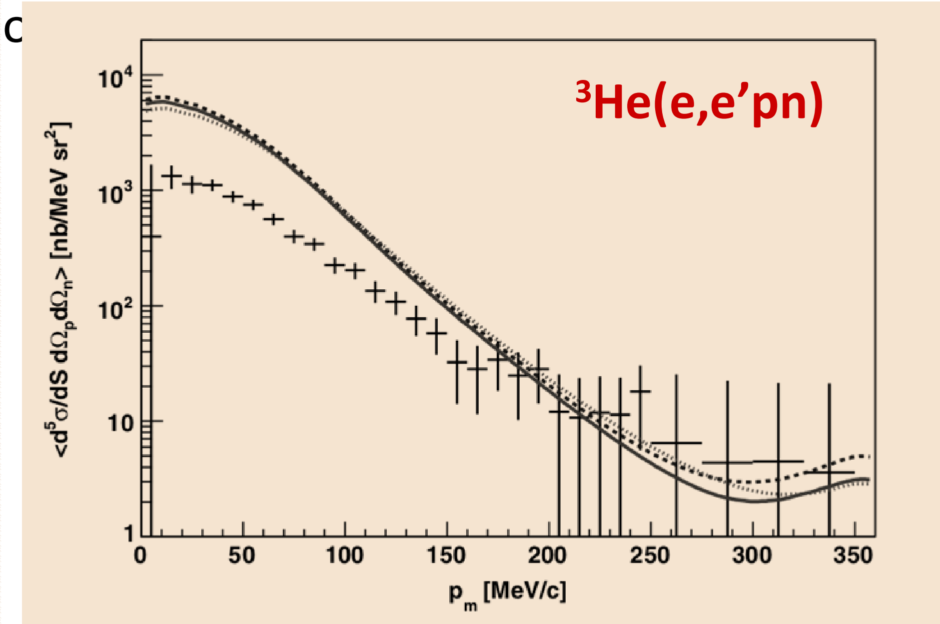


The empirical momentum distribution of the deuterons (a) and the protons (b) in ^{3}He. The solid and dashed lines are calculated with the Paris and CD-Bonn potentials, respectively. [A.Kobushkin, E.Strokovsky, PRC **87**, 024002 (2013)]

- In recent years the experimentalists were able to study in detail the pair nucleonic correlations in few-body systems using high-energy electron beams (NIKHEF, Mainz, JLab, etc.) like ^{3}He(e,e'pp), ^{3}He(e,e'pn), etc., at missing momenta $p_m > 300$ MeV/c.



The averaged ^{3}He(e,e'pp) cross section as a function of missing momentum (data of NIKHEF, D.Groep *et al.*, 2000). The theoretical predictions without (solid line) and with (dashed line) pair 2*N* currents are based on full Faddeev 3*N* calculations with three-nucleon force.

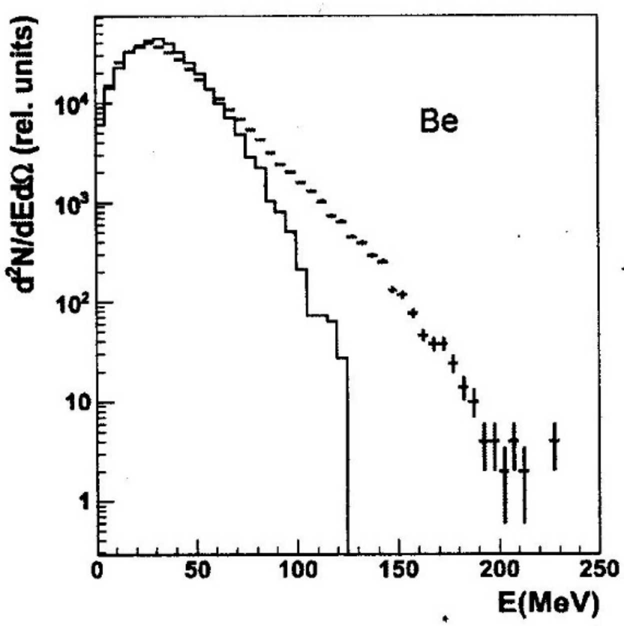


The ^{3}He(e,e'pn) reaction cross section averaged over the experimental acceptance as a function of missing momentum (Data of MAMI, D.Middleton *et al.*, 2009). Solid (dotted) line – theoretical cross section calculated using only a one-body hadronic current operator and the AV18 (Bonn) *NN* potential. Dashed line – for AV18 potential when MECs are also included.

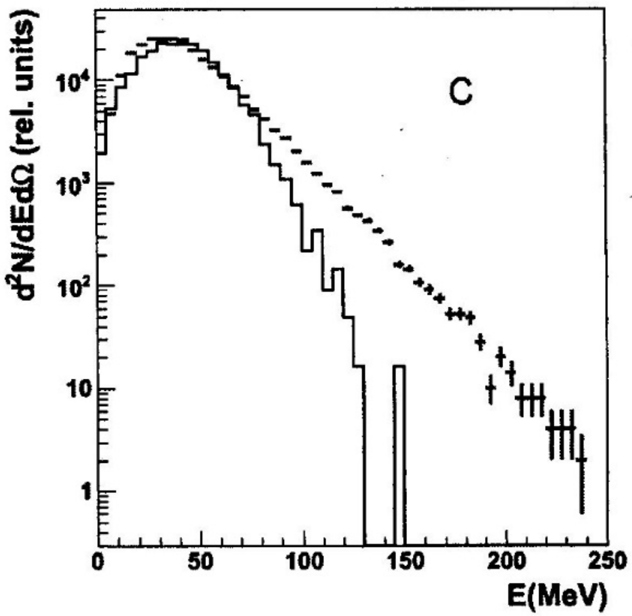
But it seems that the problem is not only in the magnitude of the repulsive core, but in our wrong interpretation of the general properties of nuclear matter and specific nuclei.

RADIAL FLOW IN COLLISIONS OF RELATIVISTIC DEUTERON AND HELIUM IONS WITH GOLD TARGET

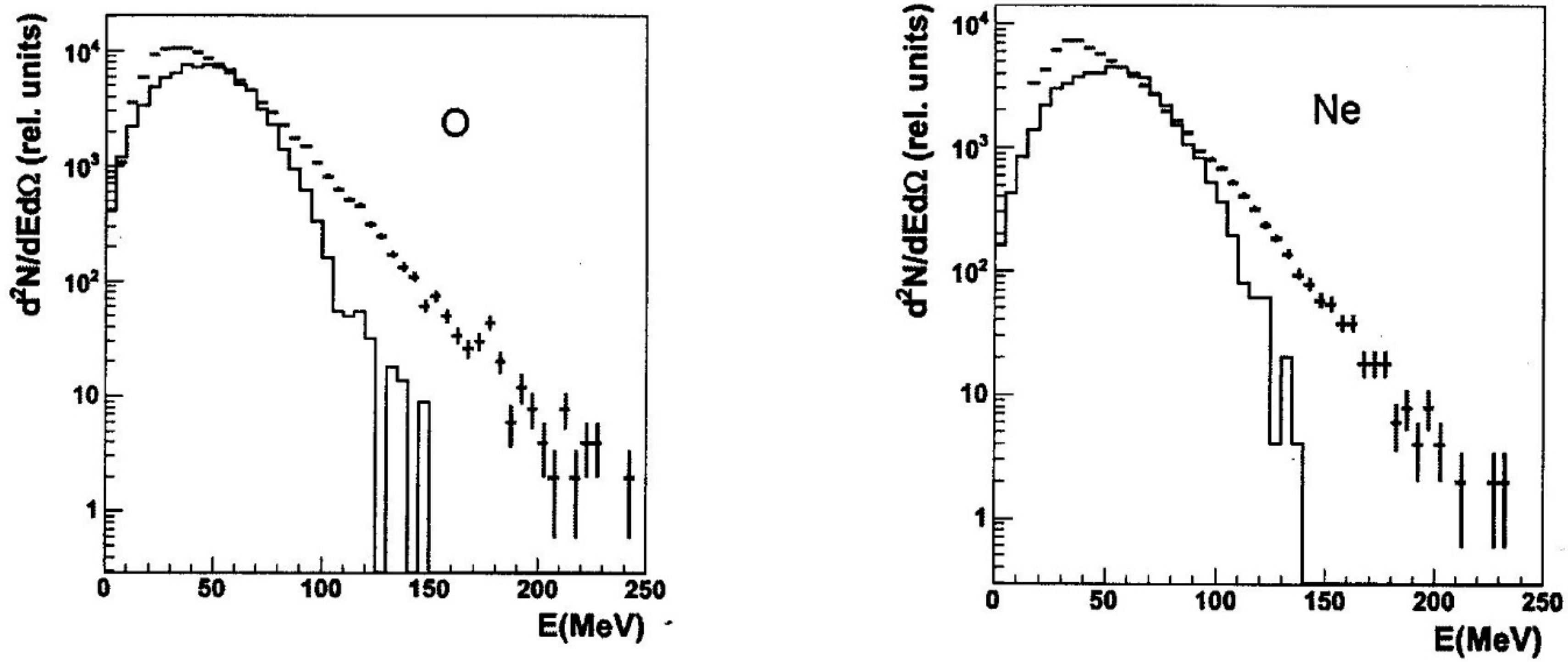
V.A. Karnaukhov, S.P. Avdeyev, Y. Oeschler, V.V. Kirakosyan, P.A. Rukoyatkin, A. Budzanowski, W. Karcz, E. Norbeck, A.S. Botvina



3



Kinetic energy spectra of Be and C produced in d(4.4 GeV)+Au collisions. Lines are calculated within the combined model INC+Exp+SMM.



Kinetic energy spectra of oxygen and neon produced in d(4.4 GeV)+Au collisions. Lines are calculated within the combined model INC+Exp+SMM.

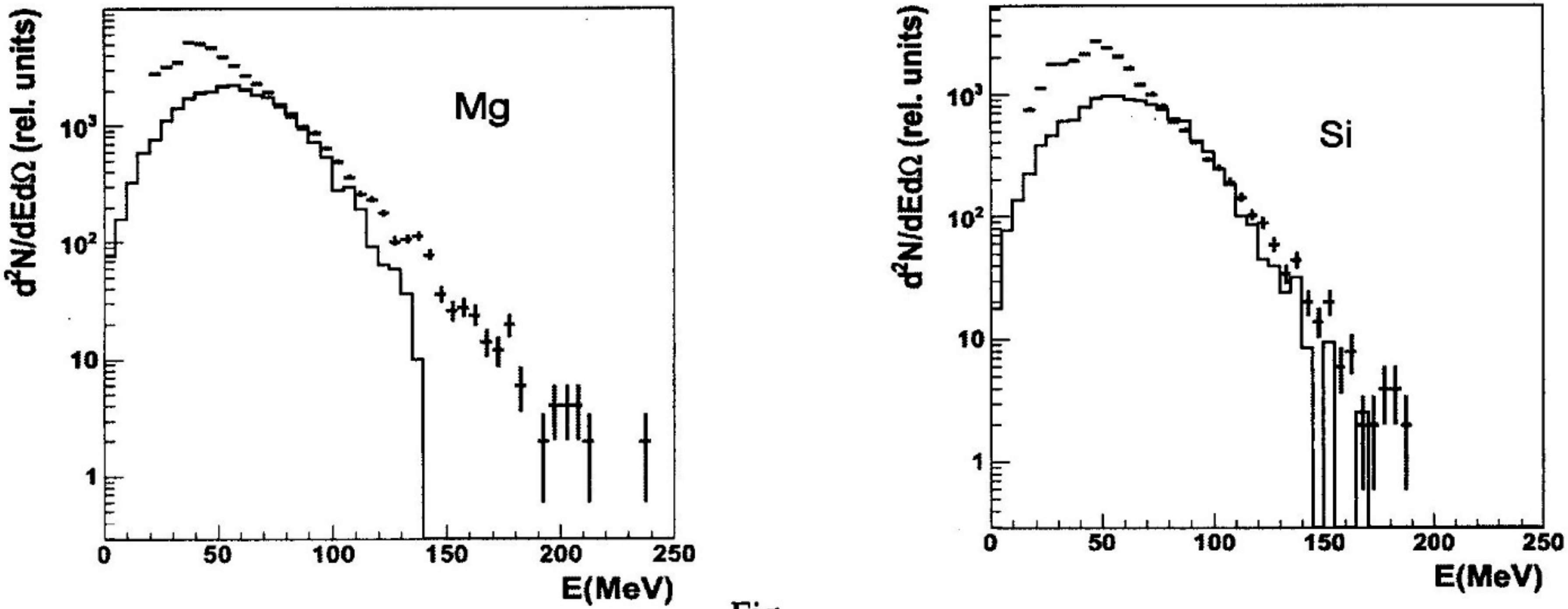
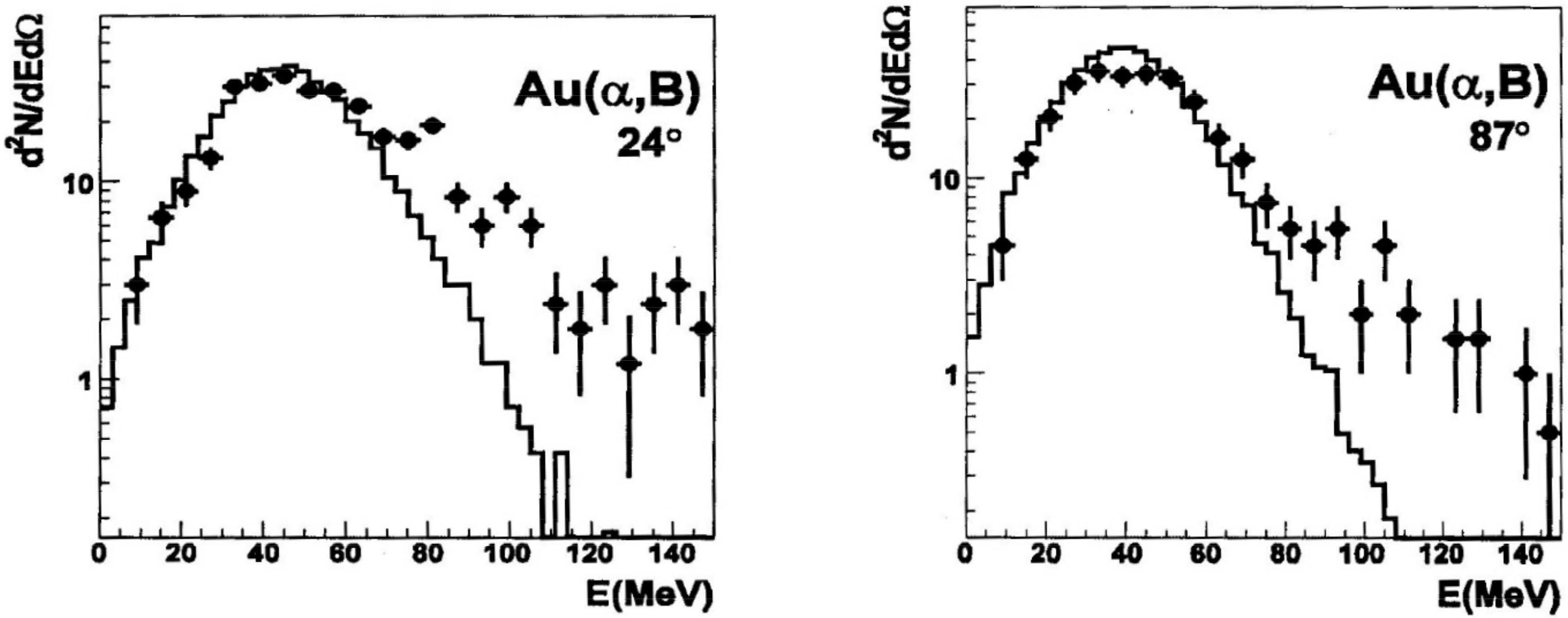


Fig.

Kinetic energy spectra of fragments with Z=12 and 14 produced in d(4.4 GeV)+Au collisions. Lines are calculated within the combined model INC+Exp+SMM.



Kinetic energy spectra of boron from fragmentation induced in Au target by helium projectile with energy 4 GeV. Lines are calculated within the combined model INC+Exp+SMM.

These experimental results look like the nucleons in nuclei (all or a part of them) have a higher temperature than that predicted by conventional nuclear models.

In turn, it implies that an averaged attraction among nucleons in nuclei is also higher than the traditional nuclear models predict. Otherwise balance between repulsive and attractive contributions would be destroyed!

This important conclusion can be further supported by the very numerous experimental studies for:

- cumulative production of mesons and other particles in high-energy hadronic collisions;
- subthreshold meson production in nucleon-nucleus and nucleus-nucleus collisions;
- EMC and DIS effects;
- and many other experiments.

Experimental studies of short-range correlations in nuclei

$$\boxed{p \geq 300 \ \text{MeV}/c}$$

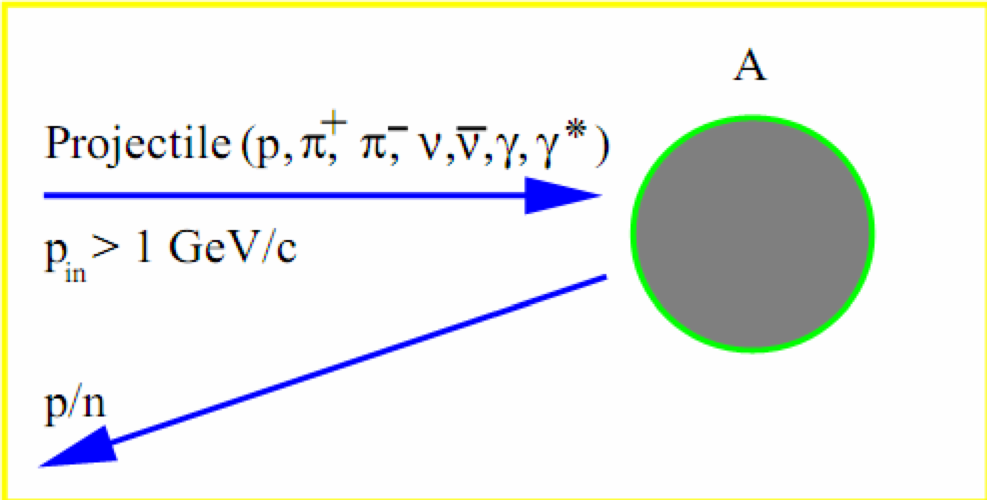
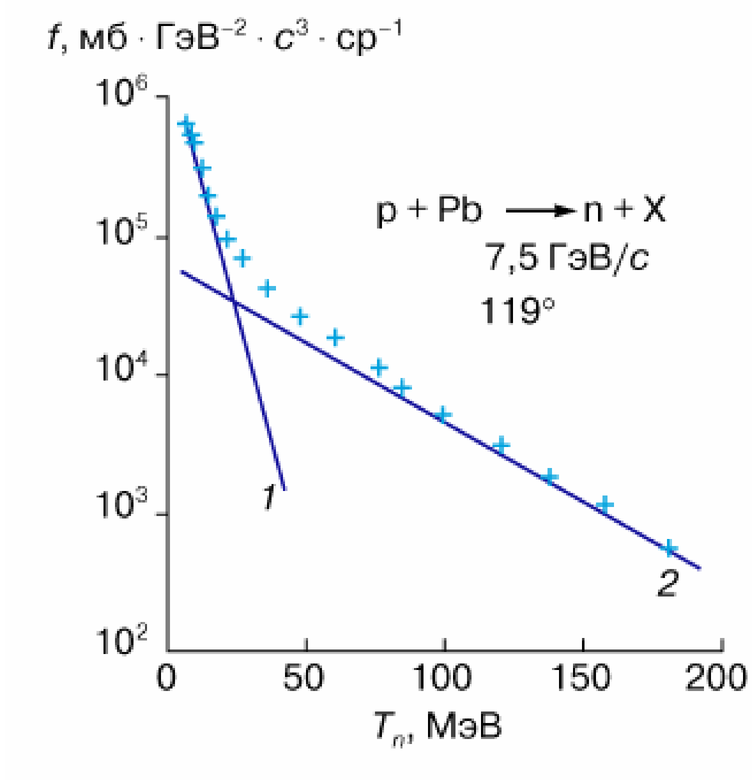


Figure 1.1: Kinematics of backward emitted nucleons.

First experiments on cumulative particles production in high-energy collisions

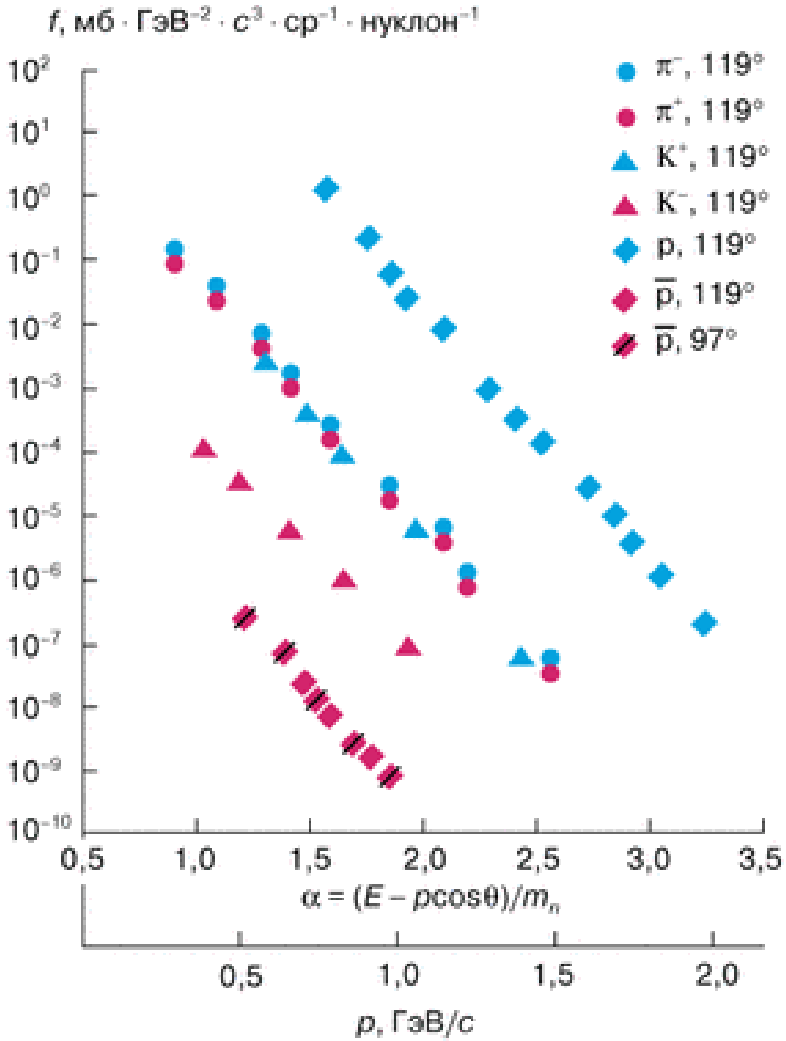
(A.M. Baldin, G.A. Leksin, *et al.*, 1950–60ies)

<u>Scattering of fast particles off nuclei at large angles in lab. system</u>



Dependence of invariant function of cumulative neutrons (proportional to neutron yield) on the neutron kinetic energy: 1 – "evaporating" neutrons, 2 – cumulative neutrons.

Production of fast cumulative particles at large angles



The dependence of invariant functions for production of different cumulative particles (π-, π+, K-, K+, etc.) on value of α (effective mass of multibaryons in target nucleus which participate in the process).

Other experiments on cumulative particles production

PHYSICAL REVIEW C VOLUME 18, NUMBER 4 OCTOBER 1978

Backward positive pion production from nuclei bombarded with 600 MeV protons, 700 MeV alpha particles, and 350 MeV deuterons

C. F. Perdrisat
Department of Physics, College of William and Mary, Williamsburg, Viriginia 23185

S. Frankel and W. Frati
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104

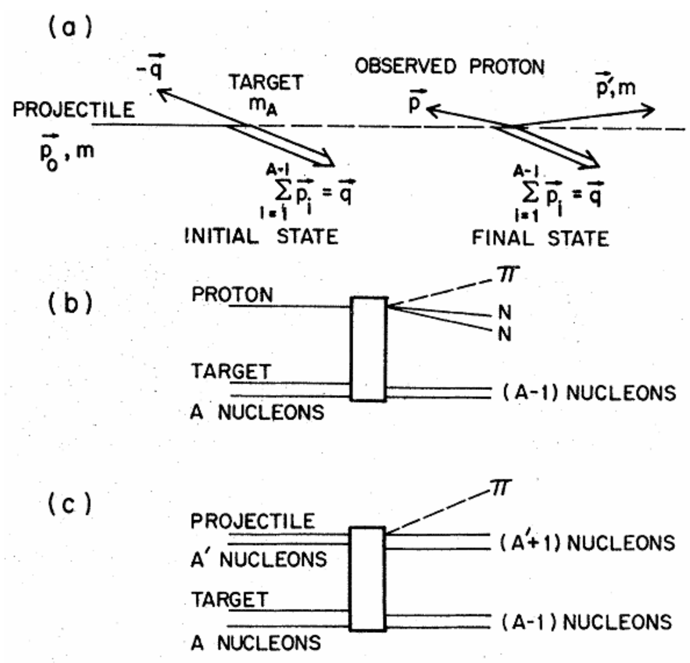


FIG. 4. (a) Kinematics for quasi-two-body scaling discussed in Sec. IV, as it applies to backward proton emission. (b) Final state in the production of one pion by a proton incoming on a complex nucleus of atomic number A. (c) Final state postulated in the modified quasi-two-body scaling for backward pion emission.

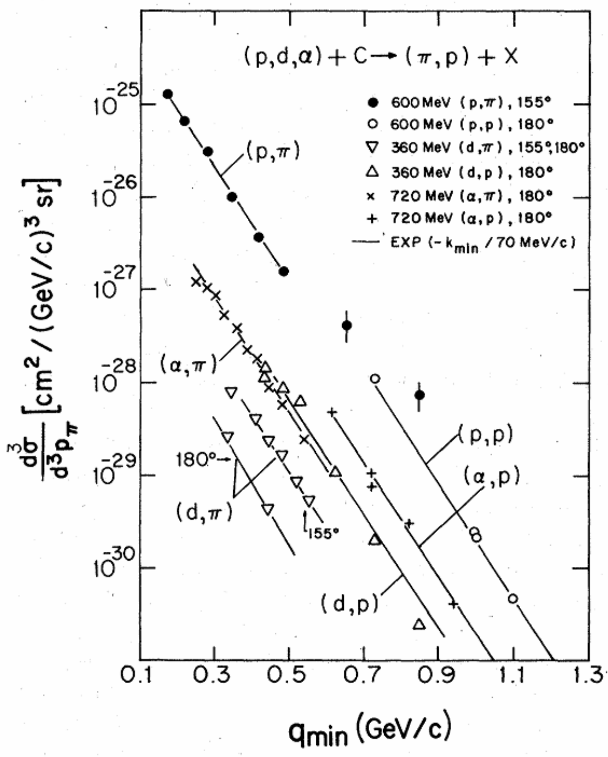


FIG. 5. Inclusive cross section $d^3\sigma/d\Omega_\pi p_\pi{}^2 dp_\pi$ vs minimum recoil q_{min} for C(p,π), C(α,π), and C(d,π), compared with results of Ref. 10 for C(p,p), C(α,p), and C(d,p). The p, α, and d energies are the same in the π- and p-production data.

Other experiments on cumulative particles production

PHYSICAL REVIEW C VOLUME 18, NUMBER 4 OCTOBER 1978

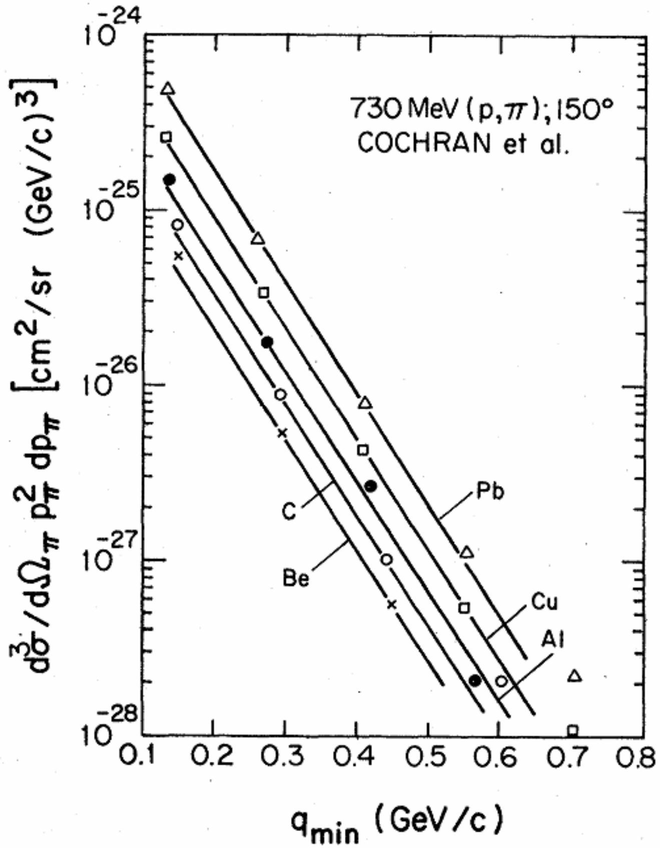


FIG. 6. Results of Cochran *et al*. (Ref. 7) for 730 MeV protons, pions at 150° represented vs q_{min}. The straight lines have a slope of 68 MeV/c and are only eyeball fits. The (✕) are for Be, (o) for C, (•) for Al, ( ) for Cu, and (▵) for Pb.

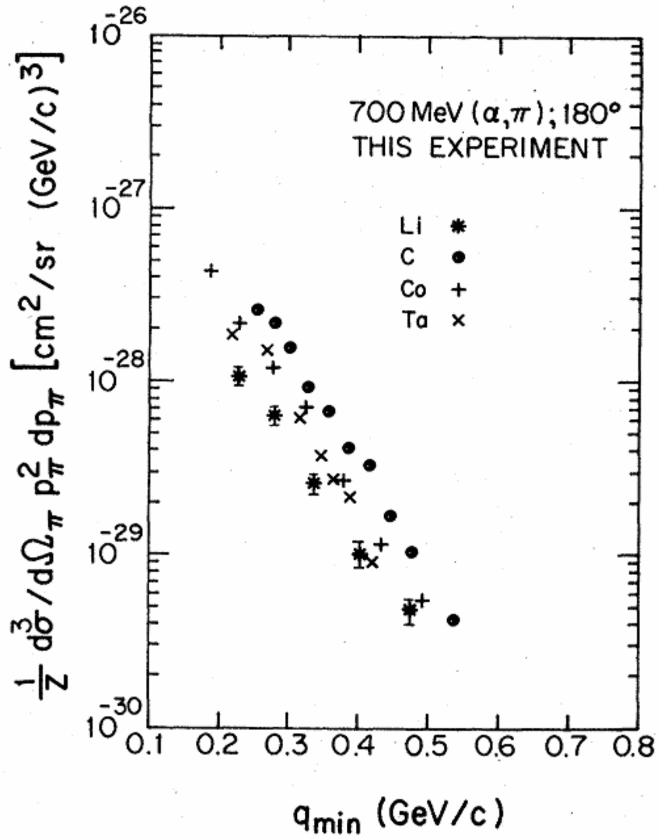


FIG. 7. Inclusive cross section $d^3\sigma/d\Omega_\pi p_\pi{}^2 dp_\pi$ multiplied by $(1/Z)$ as a function of q_{min} for (α,π) on ^{6}Li(*), C(o), Co(+), and Ta(✕), for 155° pions and 700 MeV α particles.

All these experimental data do require an enhanced high-momentum components of nuclear wave functions!

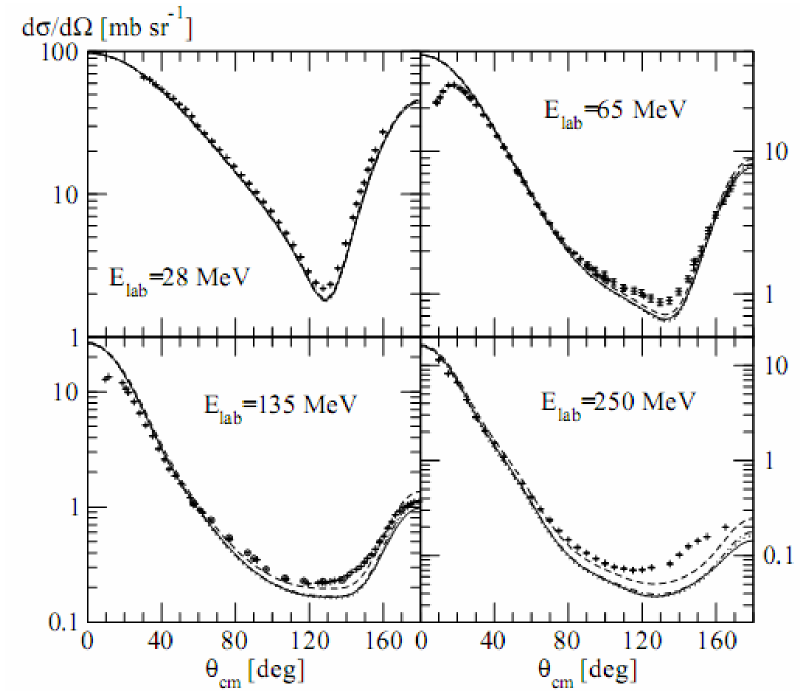
So, we need somewhat more powerful than a simple repulsive core to enhance the high-momentum components in nuclear wave functions.

The concept of dibaryons in nuclear force seems to give the needed tool for such an enhancement.

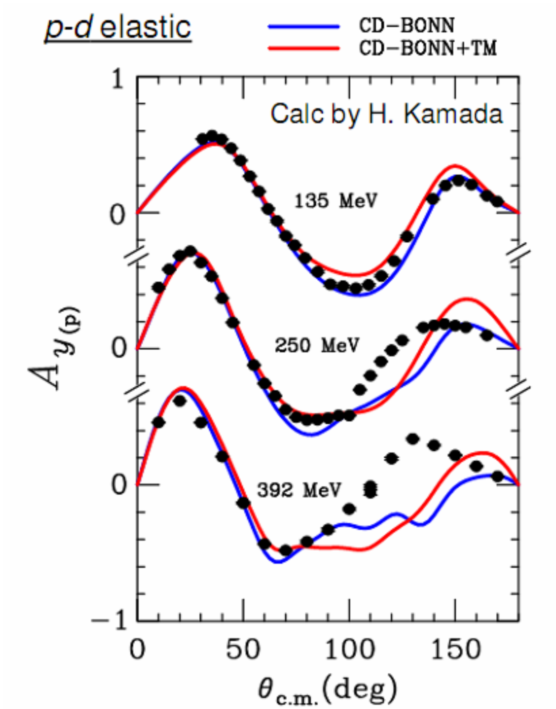
The dibaryon concept does not follow directly from the quark model but is tightly interrelated to both quarks and strings.

Recent experimental results which demonstrate the failure of the conventional mechanisms to describe short-range correlations

- At nucleon momenta in ^{3}He above k_{max} ≈ 250 MeV/c the experimental cross sections are considerably larger than predictions of theoretical models which make use the traditional *NN* and 3*N* forces. The same story we observe in ^{4}He, etc.
- On the other hand, one can analyze the level of agreement between the traditional 2*N* and 3*N* model predictions and the respective experimental data when the collision energy is rising (in this case we probe the more and more short-distance area).



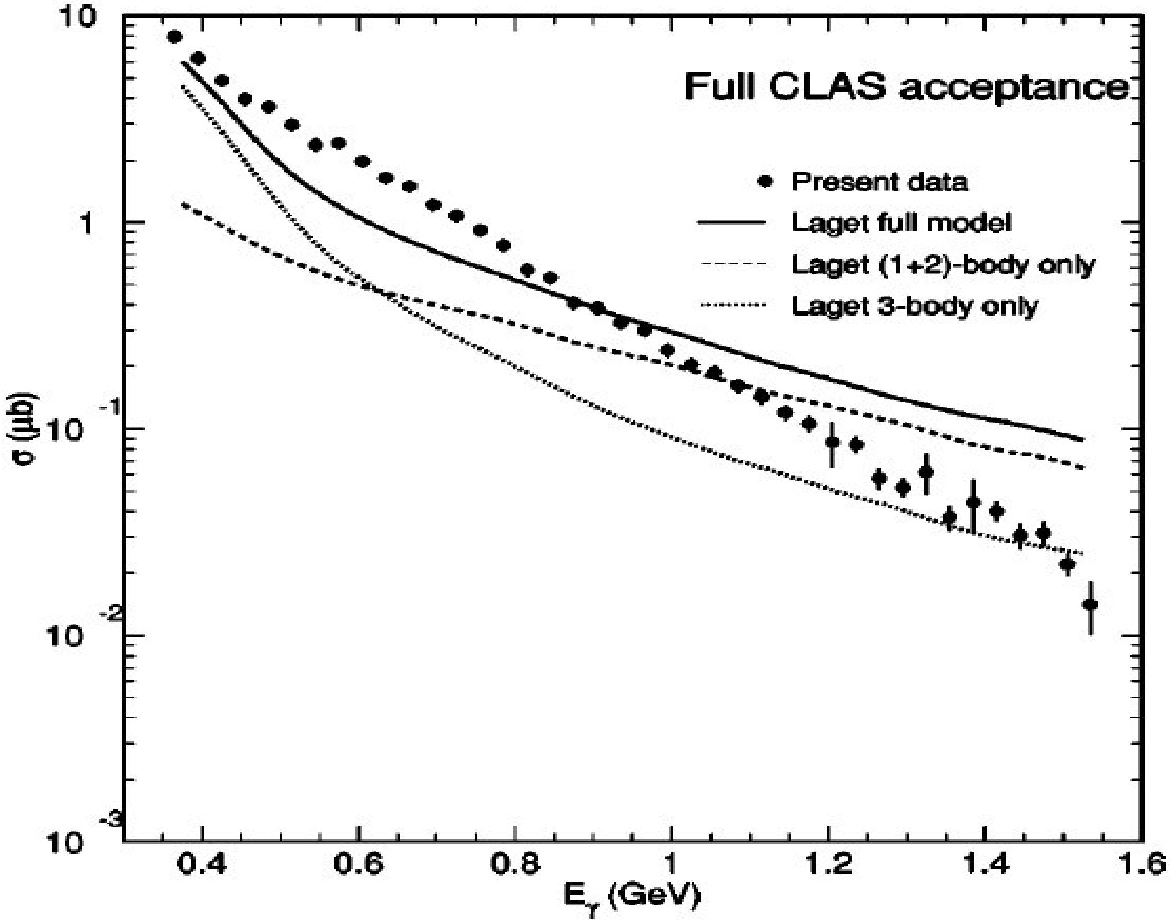
Differential cross sections for *N*d elastic scattering. Solid line – nonrelativistic Faddeev calculation using AV18 potential. Other lines – some relativistic effects added [H.Witala *et al.*, PRC **71**, 054001 (2005)]



K. Ermisch et al., PRL86(2001)5862
K. Hatanaka et al., PRC66(2002)044002
A. Tamii et al., in proc. of SPIN2006

Proton analyzing power in pd elastic scattering

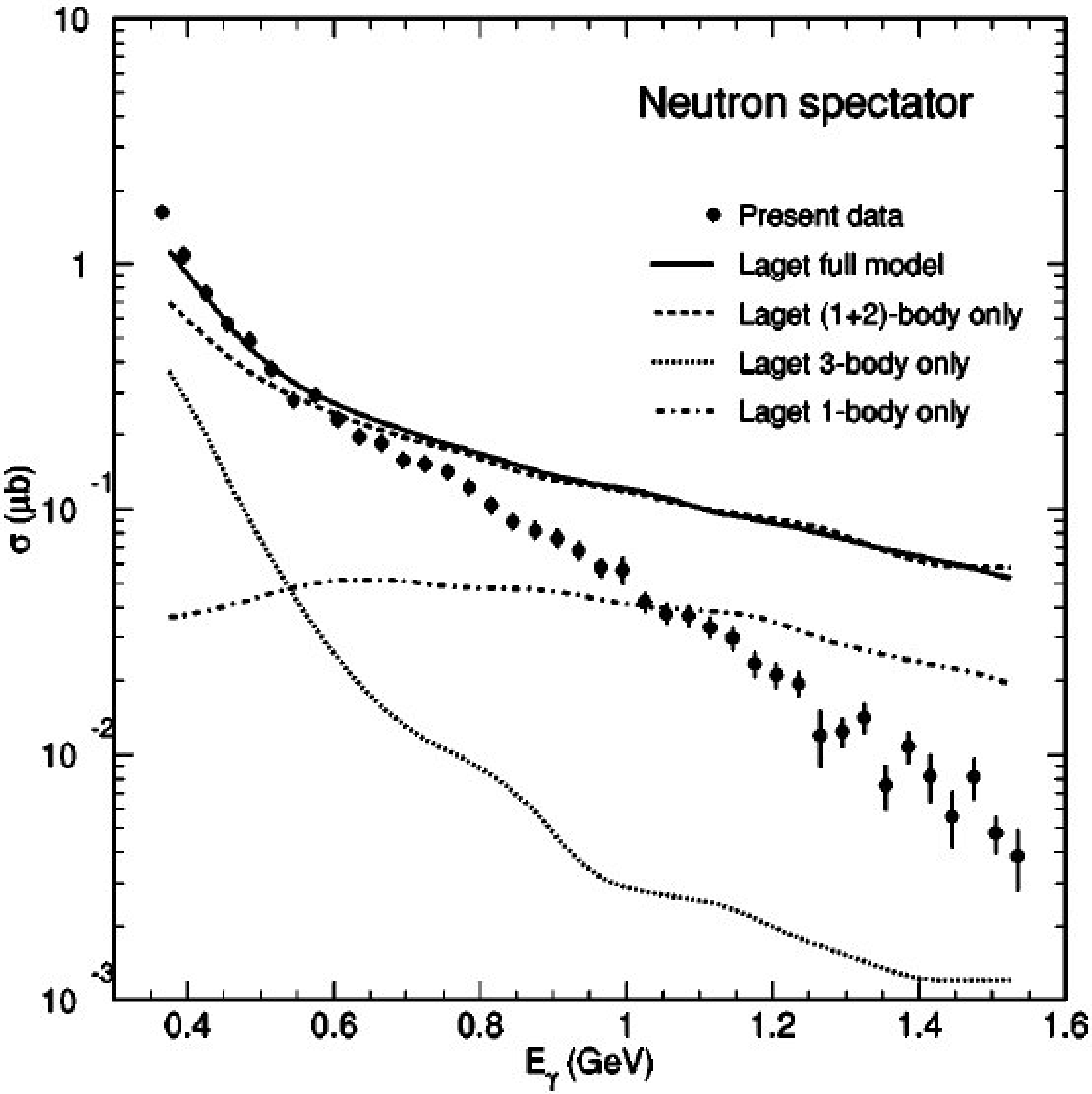
^{3}He(γ,*np*)*p* experiment vs. theory



Data of JLab [S. Niccolai *et al*., PRC **70**, 064003 (2004)]

Total ppn cross section integrated over the CLAS acceptance plotted as a function of photon energy on a logarithmic scale for the full E_γ range. The ppn cross section (circles) is compared with Laget's full model (solid curve), with the model result without the three-body mechanisms (dashed curve).

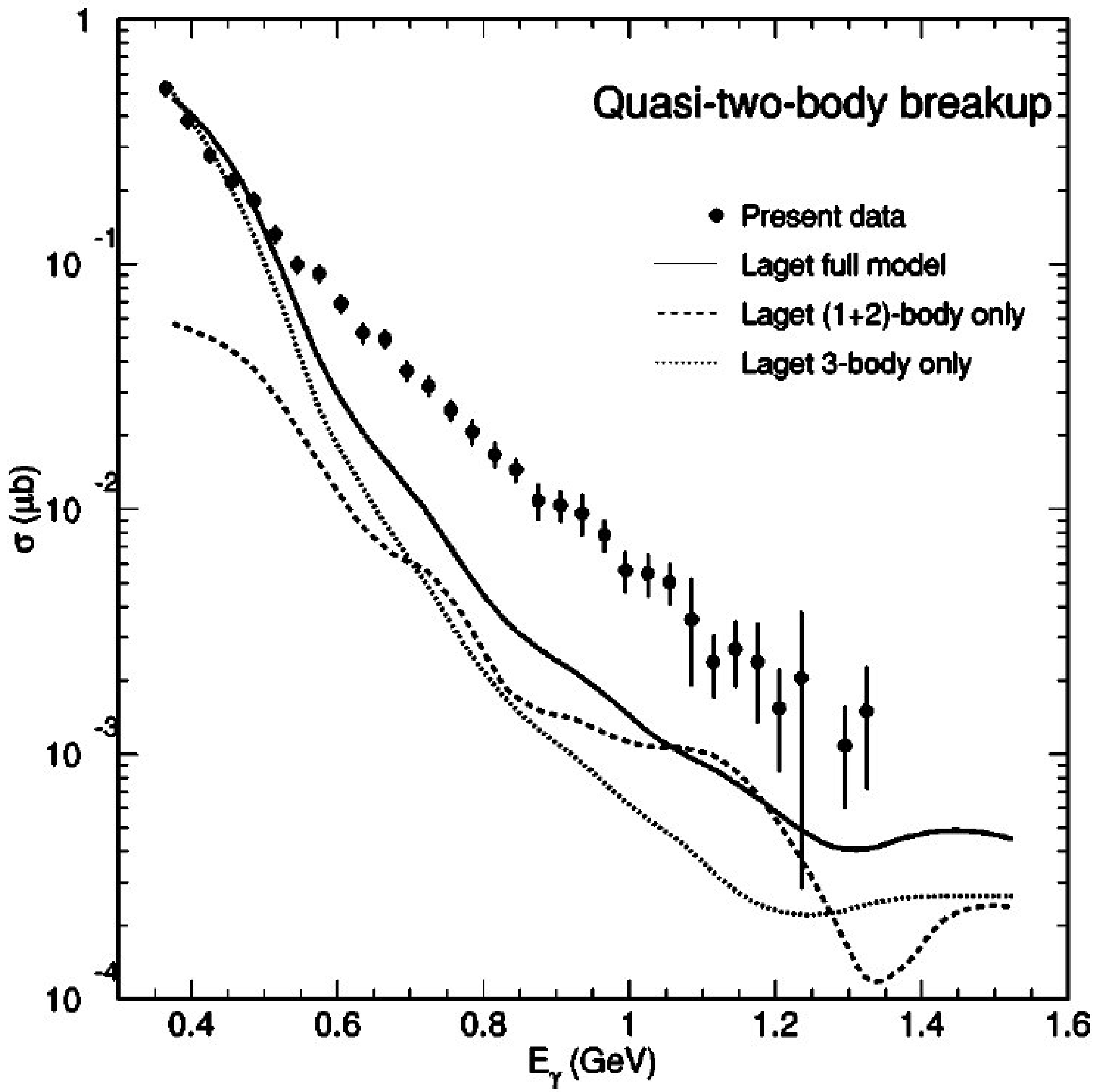
^{3}He(γ,*np*)*p* experiment vs. theory



Data of JLab [S. Niccolai *et al*., PRC **70**, 064003 (2004)]

Cross sections integrated over the CLAS for the neutron-spectator kinematics plotted as a function of photon energy.

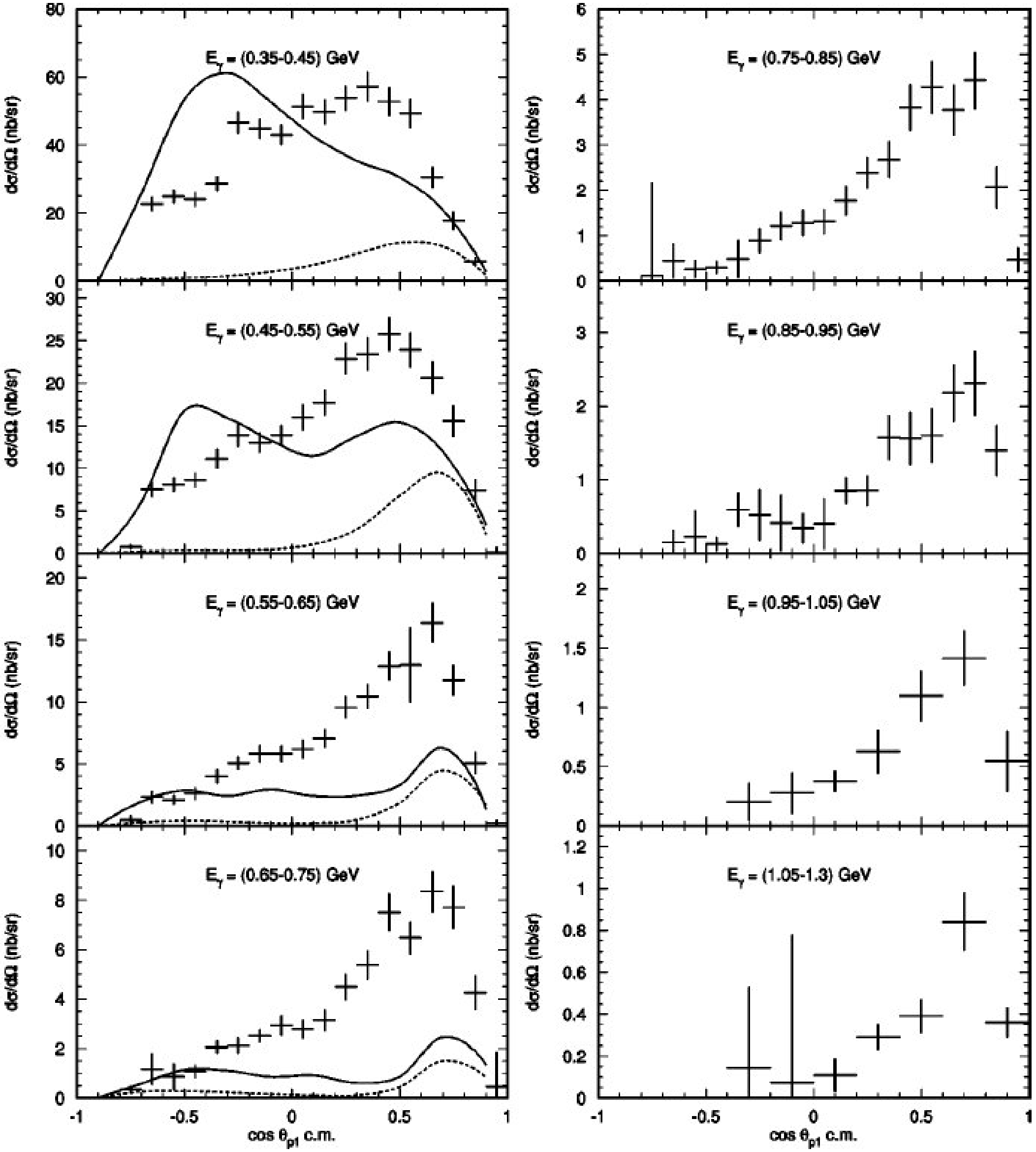
^{3}He(γ,*np*)*p* experiment vs. theory



Data of JLab [S. Niccolai *et al*., PRC **70**, 064003 (2004)]

Cross sections integrated over the CLAS for the quasi-two-body breakup plotted as a function of photon energy. The data are compared with the results of the full model (solid curves) and of the (1+2)-body-only model (dashed curves). The full-model calculation agrees quantitatively with the experimental results only up to about 0.55 GeV.

^{3}He(γ,*np*)*p* experiment vs. theory



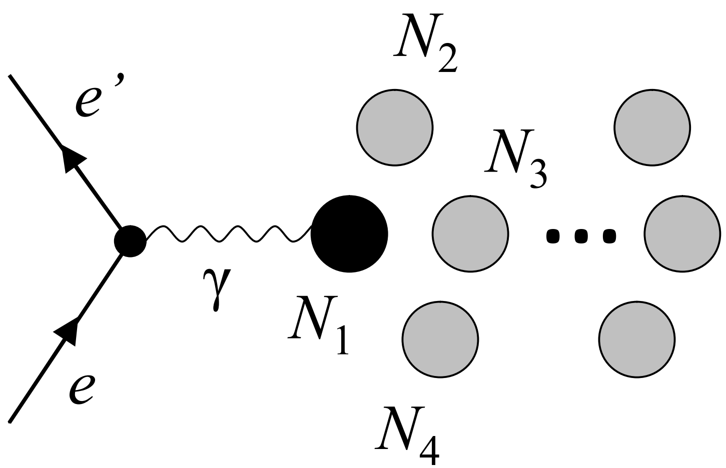
Differential cross sections integrated over the CLAS for the quasi-two-body breakup of the high-energy proton in the center-of-mass frame for photon energies between 0.35 and 1.30 GeV. The data, for $0.35 < E_\gamma < 0.75$ GeV, are compared with the results of the full model (solid curves) and of the (1+2)-body-only model (dashed curves).

Data of JLab [S. Niccolai *et al*., PRC **70**, 064003 (2004)]

Thus, the modern situation with description of short-range correlations is far from being satisfactory!

- The root of all these problems with description of high-momentum components in basic interaction or in nuclear wavefunctions seems rather evident:

  In traditional picture the fast nucleon (which interacts first with high-energy probe) cannot share effectively (i.e., with a high probability) the high momentum with other nucleons in a nucleus, using the conventional meson-exchange mechanism.



- Failure with description of $^3He(e,e'pp)$, $^3He(e,e'pn)$, etc., demonstrates this very clearly (3*N* final state rescatterings have been included in theoretical calculations).

- Thus, the short-range $2N$ and $3N$ interactions must be much stronger as compared to the traditional meson-exchange model.

- **The dibaryon mechanism is ideally suited for this because:**

– the color string inside the dibaryon can transmit a huge momentum which is incomparable with a conventional meson exchange;

– dibaryon is not a simple $6q$ bag but some “long-lived” resonance ($\Gamma_D \leq 100$ MeV, while $\Gamma_\Delta = 120$ MeV); using this resonance-like enhancement the color string can transmit a very high momentum (see below).

- There are also some implicit but very clear indications in favor of just dibaryon mechanism for short-range *NN* interaction.

  They are related to the cut-off parameters $\Lambda_{\pi NN}$, $\Lambda_{\pi N\Delta}$, $\Lambda_{\rho NN}$, etc., in form factors of the π*NN*, π*N*Δ, ρ*NN*, etc., vertices.

- In OBE-like models one chooses usually these cut-off parameters **Λ ~ 1.2 – 1.5 GeV/*c***.

  Such values of Λ's correspond to a very short radius **(*r* ~ 0.15 fm!)** of the π*N*, ρ*N*, etc., interactions which contradicts to both fundamental QCD-based approaches and experimental data. So, such very high Λ-values imitate somehow the strong short-range interaction, especially of tensor nature.

Modern experimental status of dibaryons

First prediction of dibaryon states in *NN* system

- F.J. Dyson and N.-H. Xuong, PRL **13**, 815 (1964):
  Theoretical prediction of 6 zero-strangeness low-lying dibaryons
  (on the basis of SU(6) symmetry)

Table I. $Y = 2$ states with zero strangeness predicted by the $\underline{490}$ multiplet.

Particle	T	J	SU(3) multiplet	Comment	Predicted mass
D_{01}	0	1	$\underline{10^*}$	Deuteron	A
D_{10}	1	0	$\underline{27}$	Deuteron singlet state	A
D_{12}	1	2	$\underline{27}$	S-wave N-N^* resonance	$A+6B$
D_{21}	2	1	$\underline{35}$	Charge-3 resonance	$A+6B$
D_{03}	0	3	$\underline{10^*}$	S-wave N^*-N^* resonance	$A+10B$
D_{30}	3	0	$\underline{28}$	Charge-4 resonance	$A+10B$

- The deuteron $D_{01}(1876)$ is the lowest dibaryon state strongly coupled to NN S-wave channel.
- SU(6) mass formula: $M = A+B[T(T+1)+J(J+1)-2]$ (A – deuteron mass, $B \approx 47$ MeV)
  Prediction for masses of N-Δ and Δ-Δ S-wave resonances:

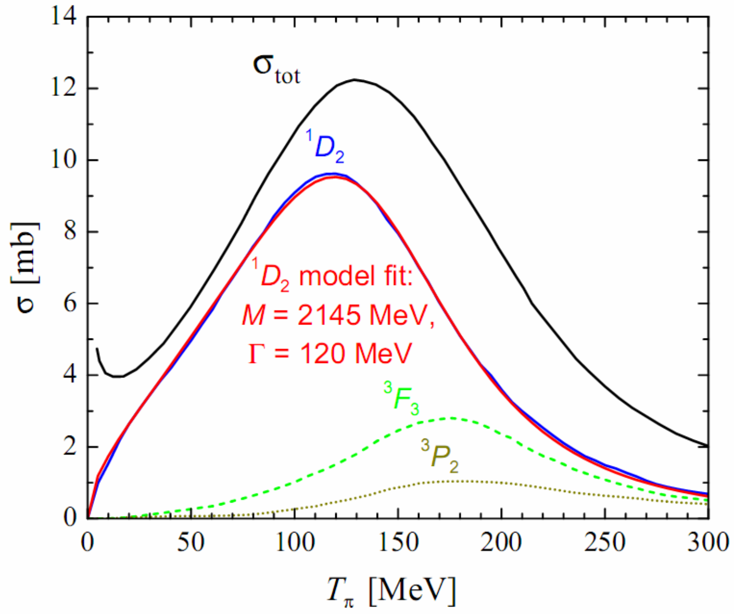
$$M(D_{12}) \approx 2160 \text{ MeV} \approx M(N) + M(\Delta) - 10 \text{ MeV},$$
$$M(D_{03}) \approx 2350 \text{ MeV} \approx M(\Delta) + M(\Delta) - 110 \text{ MeV}.$$

Indications of D_{12} and other isovector dibaryons

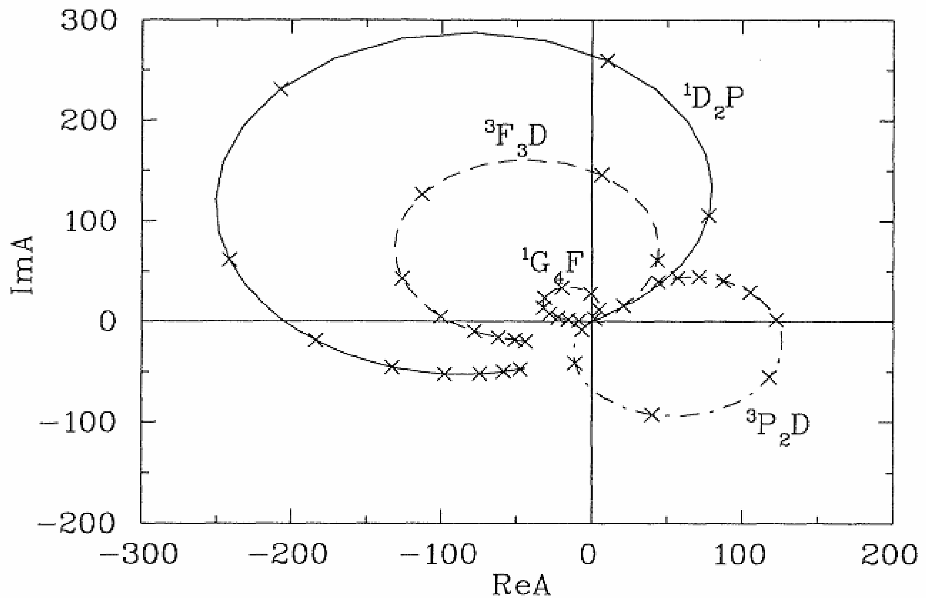
- Experiments on $\vec{p}+\vec{p}$ elastic scattering (I. Auer et al., 1978) and partial wave analyses (PWA) for $pp \to pp$, $\pi^+d \to \pi^+d$ and $\pi^+d \to pp$ (N. Hoshizaki, 1979, 1993; R. Arndt et al., 1981, 1993; etc.) revealed the series of isovector resonances in NN channels $^1D_2$, $^3F_3$, $^1G_4$, etc.
- The lowest ($^1D_2$) isovector resonance: $I(J^P) = 1(2^+)$,

  $M \approx 2140–2160$ MeV $\approx M(N{+}\Delta)$ - (10–30 MeV), $\Gamma \approx 100–120$ MeV $\approx \Gamma(\Delta)$.

Contributions of the dominant ^1D_2P, ^3F_3D and ^3P_2D amplitudes to the $\pi^+d \to pp$ total cross section



Argand plot of the dominant partial-wave amplitudes in $\pi^+d \to pp$

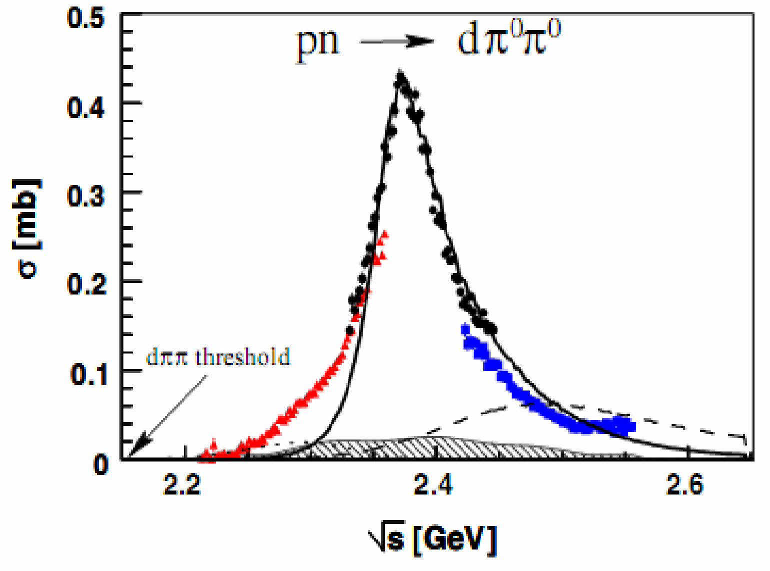


- True resonances or "pseudoresonances" (intermediate $N{+}\Delta$ states)?

New evidence for isoscalar D_{03} dibaryon

- Recently the WASA@COSY Collaboration (Jülich) completed the large series of experiments on 2π-production reactions in p+n, p+d and d+d collisions at intermediate energies (E ~ 0.7–1.7 GeV).

- They found an **unambiguous dibaryon resonance signal** in p+n collisions at $T_p \sim$ 1–1.4 GeV in 2π -production cross section [P. Adlarson *et al.*, PRL **106**, 242302 (2011)].



$$I(J^P) = 0(3^+)$$
$$M_R \approx 2.37\ \text{GeV}$$
$$\Gamma_R \approx 70\ \text{MeV}$$

- So, this resonance is located just only 70 MeV below the ΔΔ threshold and can be treated in a model of ΔΔ near-threshold bound state.

Evidence for D_{03} dibaryon from n+p elastic scattering

PRL 112, 202301 (2014) PHYSICAL REVIEW LETTERS week ending 23 MAY 2014

Evidence for a New Resonance from Polarized Neutron-Proton Scattering

(WASA-at-COSY Collaboration) & (SAID Data Analysis Center)

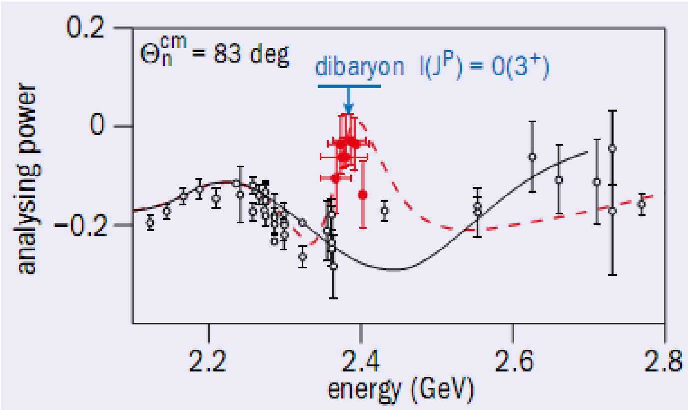
CERN Courier July/August 2014

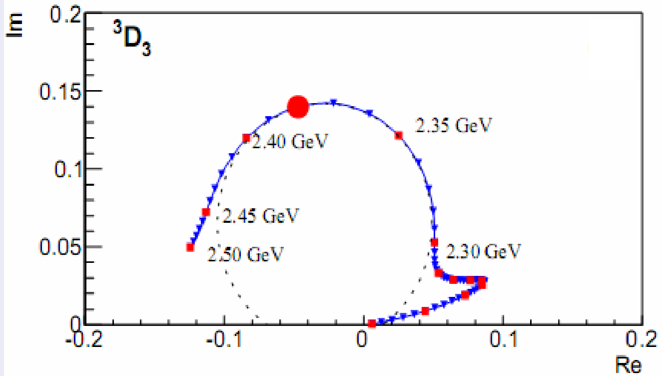
$$\boxed{(\sqrt{s})_{\text{pole}} = 2380 \pm 10 - i40 \pm 5\ \text{MeV}}$$

News

NEW PARTICLES

COSY confirms existence of six-quark states





——— SAID SP07 (2007) – – – new PWA solution (2014)

$D_{03} \approx \Delta\Delta(30\%) + C\bar{C}(70\%)$ [F. Huang et al., nucl-th/1505.05395; see also M. Bashkanov, S. Brodsky, H. Clement, PLB727(2013)438]

- R.m.s. radius $r(D_{03}) \approx$ **0.7–0.9 fm** (from microscopic quark model calculations)
- Full width $\Gamma(D_{03}) = 70 - 90\ \text{MeV} \ll 2\Gamma(\Delta) = 235\ \text{MeV}$

D_{03} resonance appears to be the ***truly dibaryon (6q) state*** coupled to $\Delta\Delta$ channel and not only the $\Delta\Delta$ bound state!

Additional confirmation of D_{12} and D_{03} resonances

- From solving exact Faddeev equations for πNN and $\pi N\Delta$ systems the robust dibaryon poles corresponding to D_{12} and D_{03} were found:

$$\boxed{M(D_{12}) = 2151 \pm 2\ \mathrm{MeV}, \quad \Gamma(D_{12}) = 120 \pm 6\ \mathrm{MeV}}$$

$$\boxed{M(D_{03}) = 2363 \pm 20\ \mathrm{MeV}, \quad \Gamma(D_{03}) = 65 \pm 17\ \mathrm{MeV}}$$

[A. Gal, H. Garcilazo, PRL111(2013)172301 & NPA928(2014)73]

- Very good agreement with Dyson and Xuong predictions as well as with experimental findings.

New experiments of the COSY/ANKE Collaboration

(V. Komarov, D. Tsirkov, et al.)

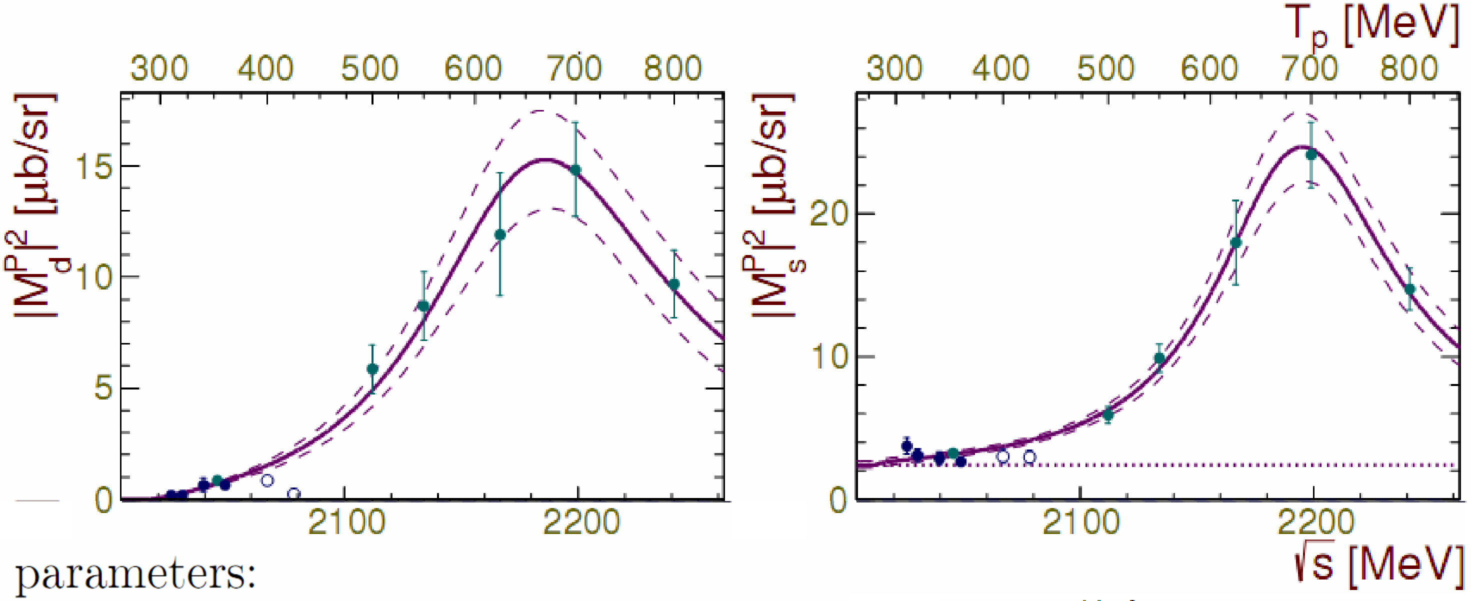
$pp \to \{pp\}_s \pi^0$

Observation of isovector dibaryon resonance-like states with a mass of 2.2 GeV$/c^2$

- Two main transitions $^3P_0 \to {}^1S_0 s$, $^3P_2 \to {}^1S_0 d$
- $\{d\sigma_0/d\Omega,\ \kappa,\ A_y^{\max}\} \longrightarrow \{|M_s^P|,\ |M_d^P|,\ \phi\}$

[D. Tsirkov, talk at 2015 European Nuclear Physics Conference, 31 August 2015, to be published]

Partial waves energy dependence



- $^3P_2$ resonance parameters:
  $E_R = 2195 \pm 8$ MeV$/c^2$, $\Gamma = 134 \pm 22$ MeV$/c^2$
  with $\chi^2/\text{ndf} = 8/6$
- Indication on resonant behaviour in $^3P_0 s$, parameters:
  $E_R = 2199 \pm 5$ MeV$/c^2$, $\Gamma = 94 \pm 11$ MeV$/c^2$,
  $c_{bg} = 2.4 \pm 0.2$ μb$/$sr
  with the $\chi^2/\text{ndf} = 6.5/6$

Nuclear force model based on dibaryon mechanism

- The main deficiency of all preceding (very numerous) treatments for NN and 3N short-range correlations in nuclei: they were not connected with the existing theory of nuclear forces.
- The enhancement of short-range correlations needed for description of a particular process was achieved *ad hoc* by means of some exotic mechanisms and was not related to the basic meson-exchange theory of NN interaction.

What is the basic meson-exchange theory of nuclear force today?

It is either:

(i) Effective field theory (EFT), or Chiral perturbative theory on a "small" parameter χ/Λ ($\Lambda \sim 1$ GeV)

or

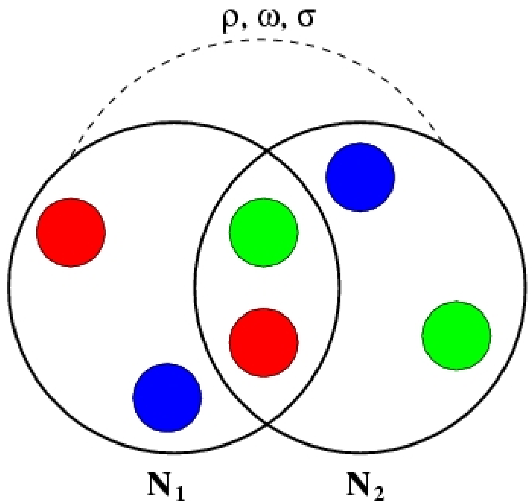
(ii) So-called realistic NN and 3N potentials (CD-Bonn, Nijmegen I&II, Argonne V18, etc.).

None of these potentials can describe properly the basic short-range effects (subthreshold meson production, cumulative processes, high ratio of pn to pp correlations in nuclei, etc.)

Thus, basic experiments on short-range correlations in nuclei do not support the conventional theories of nuclear forces.

What are dibaryons? Qualitative picture

- The short-range *NN* interaction (at r_{NN} < 1 fm) occurs in the area where two nucleons get overlapped because $\langle r_N^q \rangle \sim 0.6$ fm, and their quark cores get also overlapped.



- In such a situation the conception of meson exchange between two isolated nucleons becomes meaningless at all and the mesons from the meson clouds of two nucleons should be moving in the field of the unified six-quark core.

- Thus, the conventional assumption about the mechanism of heavy-meson exchange between two nucleons at distances r_{NN} < 1 fm looks to be completely unjustified theoretically. E.g., the wide-spread idea about existence of a local *NN* repulsive core at r_{NN} < 0.5 fm belongs to such sort of assumptions. (I'll show in the talk how to replace such a repulsive core by non-local repulsive mechanism fully compatible with the quark model.)

What are dibaryons? Qualitative picture

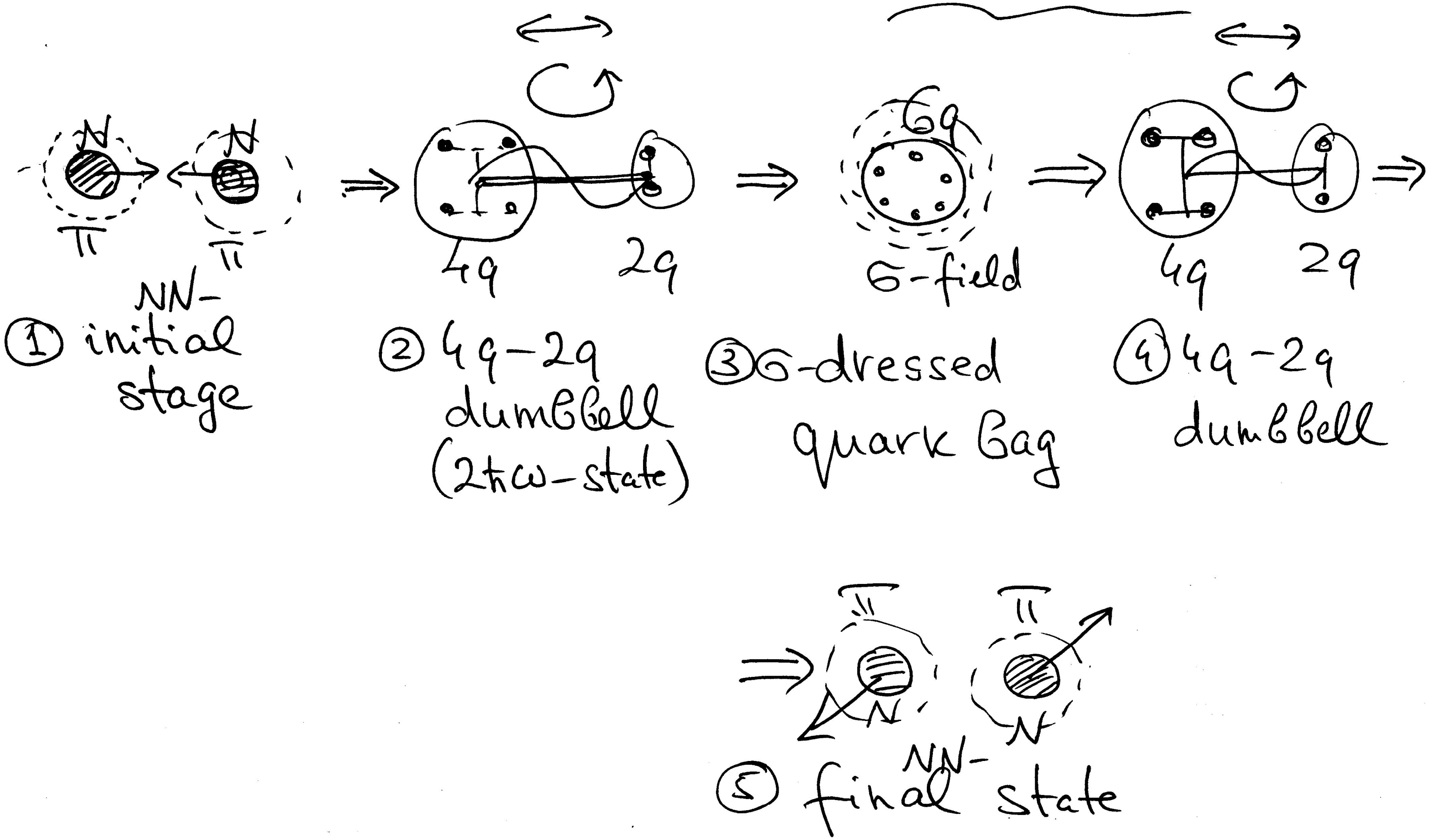
- If we start from the opposite side, i.e., by constructing an effective *NN* potential using quark microscopic model, it leads also to quite disappointing results:
  - without an assumption of phenomenological σ-meson exchange between quarks one gets purely repulsive *NN* potential at the distances $r_{NN} < 1.4$ fm;
  - moreover, if to involve phenomenologically *t*-channel σ-meson exchange between quarks taking into account the loops: $\sigma \to \pi\pi \to \sigma \ldots$, i.e., the σ-meson width, one gets also purely repulsive *NN* potential.
- Thus, the traditional six-quark model appears to be not leading to correct understanding of the short-range *NN* interaction as well.

To summarize:

We should look for some principally novel mechanism for short-range *NN* force. In view of the new reliable experimental findings (BNL, WASA@COSY, Mainz, etc.) we should change all the traditional conception for the short-range forces in 2*N* and 3*N* sectors.

What are dibaryons?
Qualitative picture

The diBaryon mechanism for NN-interaction.

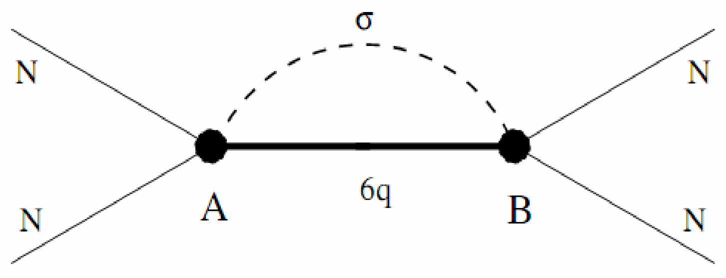


Dibaryon mechanism for intermediate- and short-range nuclear force

- The particular short-range mechanism proposed by us in 1998 [V.I. Kukulin, in *Proc. XXXIII PIYaF Winter School*, S.-Petersburg, 1998, p.207]:

$$N + N \rightarrow |s^4p^2[42]\ L_q = 0{,}2;\ ST> \rightarrow |s^6[6]\ L_q = 0,\ ST + \sigma>,$$

or in a graphic form:



- The above mechanism replaces the conventional *t*-channel σ-exchange between two nucleons (which is meaningless at r_{NN} < 1 fm) by the *s*-channel exchange of the σ-dressed dibaryon.
- The dibaryon mechanism looks to be ideally suited to describe the short-range *NN* force. It is because the mechanism assumes generation of the intermediate "long-lived" quark-meson states and such a resonance-like state will enhance somehow the short-range *NN* interaction.

- Such a mechanism, in accordance to general rules for the Feynman graphs, corresponds to a separable potential:

$$V_{NqN} \sim \lambda(E) g(\mathbf{k}) g(\mathbf{k'}),$$

where $\sqrt{\lambda(E)}g(\mathbf{k})$ corresponds to a transition vertex *NN* $\Rightarrow$ *D; g*(***k***) is proportional to the overlap of *NN* wavefunction and six-quark wavefunction with symmetry |s^4p^2[42] *L*=0,2; *ST*>, and the energy-dependent coupling constant $\lambda(E)$ corresponds to the intermediate dressed dibaryon propagation:

$$\lambda(E) = \int_0^\infty d^3k \frac{g(\mathbf{k}) g(\mathbf{k})^*}{E - m_D - k^2 / m_D - \omega_\sigma(k)}$$

- Thus, to calculate the short-range *NN* potential one needs to know only some basic parameters of the dressed six-quark bag (the mass and radius of the intermediate dibaryon [V.I.Kukulin, I.T.Obukhovsky, V.N. Pomerantsev, A. Faessler, Int. J. Mod. Phys. E **11**, 1 (2002)].

- In case of two channels ${}^3S_1$-${}^3D_1$ coupled by a short-range tensor force (which is originated from one-gluon exchange) one gets the two-channel separable potential (for non-relativistic case):

$$V_{NqN} = \begin{pmatrix} \lambda_{ss} |g_s\rangle\langle g_s| & \lambda_{sd} |g_s\rangle\langle g_d| \\ \lambda_{ds} |g_d\rangle\langle g_s| & \lambda_{dd} |g_d\rangle\langle g_d| \end{pmatrix},$$

where the vertex form factors $|g_s>$ and $|g_d>$ correspond to the six-quark wavefunctions $|s^4p^2[42]\ L=0;\ ST=10>$ and $|s^4p^2[42]\ L=2;\ ST=10>$, respectively.

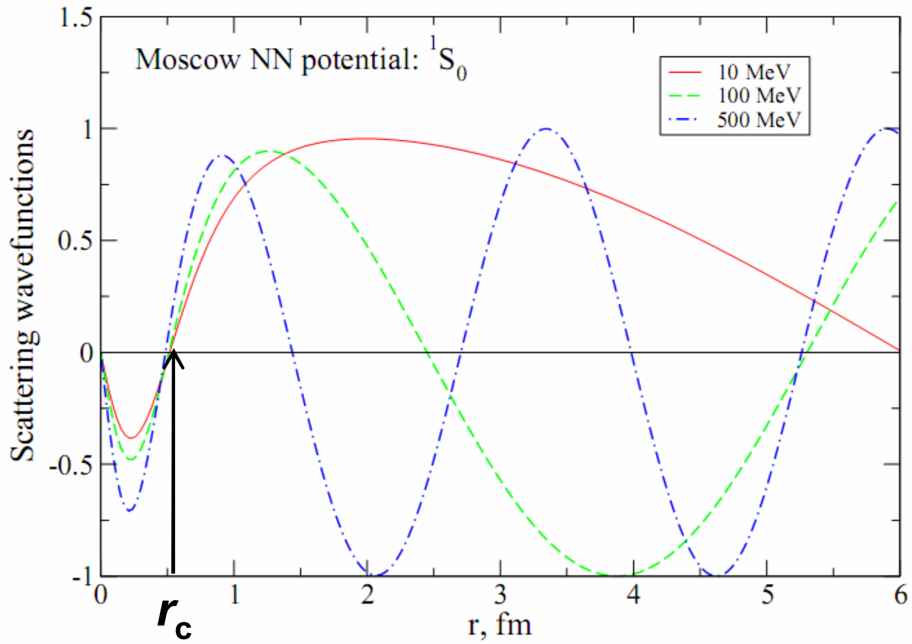
- The consistent relativistic generalization of the above dibaryon model has been presented some time ago [A.Faessler, V.I.Kukulin, M.A.Shikhalev, Ann. Phys. (N.Y.) **320**, 71 (2005)].

How the hard repulsive core effects are reproduced by the dibaryon model

- The above short-range potential V_{NqN} is operating in a six-quark space (to say more accurately, in the space of projections of the six-quark wavefunctions onto the *NN* channel) of mixed symmetry wavefunctions $|s^4p^2[42]\ LST>$ with $2\hbar\omega$ inner excitation.
- So, the projection onto the *NN* channel:

$$f(r) = <NN|s^4p^2[42]\ L=0;\ ST>$$

turns out to be a nodal function where the stationary node position at $r_n = r_c$ coincides with the hard core radius $r_c = 0.5$ fm accepted in conventional *NN* potential models when we choose the six-quark bag radius $b = 0.55$ fm in a way to reproduce the low-energy spectrum of nucleon excitations.



How the hard repulsive core effects are reproduced by the dibaryon model

- On the other hand, among many six-quark states which are possible in the *NN* system, the above dibaryon mechanism acts mainly in the mixed symmetry states, while it leads to an effective repulsion for fully symmetric six-quark configurations, like $|s^6[6]\, LST\rangle$, which corresponds to a nodeless wavefunction in the *NN* channel.

- So, one should supplement the short-range *NN* potential V_{NqN} by the projection operator $V_{\mathrm{orth}} = \mu|\varphi_0\rangle\langle\varphi_0|$ onto the nodeless *NN* wavefunction with a large positive constant μ (it is the so-called orthogonalizing pseudo-potential – OPP).

- Thus, this strongly repulsive non-local short-range potential V_{orth},which in the dibaryon model leads to appearance of a stationary node at the distance $r = r_c$ in *NN* channel, plays the role of a local repulsive core in the conventional *NN* potential models.

- At larger distances, r_{NN} > 1 fm, the short-range *NN* interaction $(V_{NqN} + V_{\rm orth})$ should be supplemented by the conventional OPE and TPE potentials.

So that, the total *NN* potential in partial waves $L_{NN} \leq 2$ takes the form:

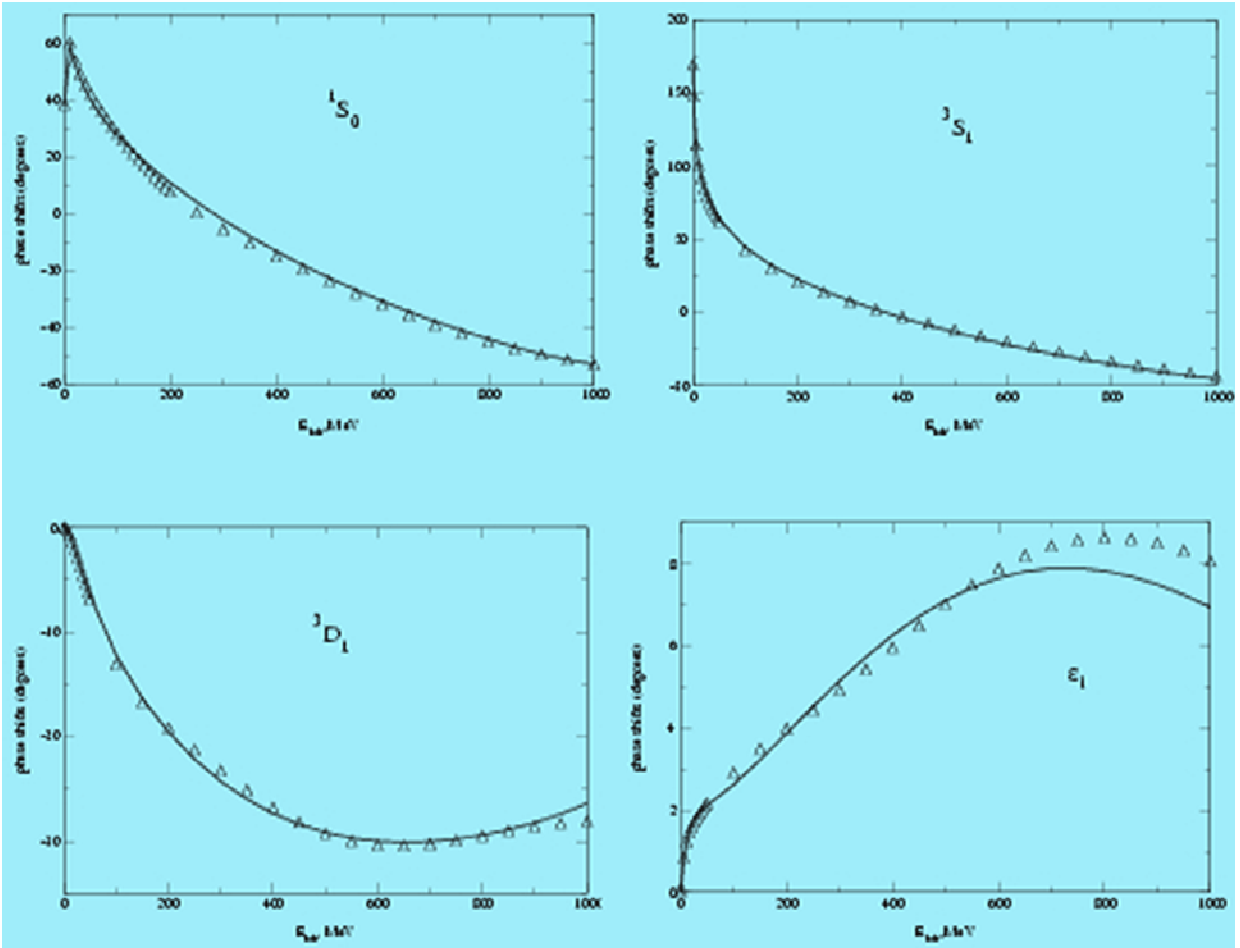
$$V^{\rm total} = \underbrace{V_{NqN} + V_{\rm orth}}_{\textit{short-range}} + \underbrace{V^{\rm OPE} + V^{\rm TPE}}_{\textit{long-range}}$$

- Now we can improve the long-range components using the potentials derived from the consistent ChPT, or, alternatively, one can replace the very numerous contact terms in ChPt with the dibaryon-model-motivated short-range part $(V_{NqN} + V_{\rm orth})$.

- It is very plausible that using such a replacement **the energy range**, where theoretical *NN* phase shifts calculated within the hybrid approach (dibaryon model + ChPT) reproduce the empirical *NN* data, **can be extended noticeably** (e.g., until $E \sim 1$ GeV and higher) and that **the number of contact terms or fit parameters can be decreased strongly**.

<u>There is a good evidence to this point</u>:

We have been able to fit our dibaryon-induced potential to empirical *NN* phase shifts in low partial waves in the energy range 0–1000 MeV (in contrast to the case of ChPT or conventional OBE models: 0–350 MeV) using only a few basic dibaryon parameters.



Testing the dibaryon force model in few-body systems

In last few years,

1) we made detailed tests for the dibaryon model;
2) we compared its basic predictions with the experimental data.

Three-nucleon system within dibaryon model

A $3N$ state Ψ_3 in the full three-body Hilbert space $\mathcal{H}_3 = \mathcal{H}_3^{\rm ex} \oplus \Sigma_i \mathcal{H}_i^{\rm in}$ is a four-component column and the total Hamiltonian of the three-body system acting in $\mathcal{H}_3$ can be written as (4×4) matrix:

$$\Psi_3 = \begin{pmatrix} \Psi^{\rm NN} \\ \Psi_1^{\rm DN} \\ \Psi_2^{\rm DN} \\ \Psi_3^{\rm DN} \end{pmatrix}, \qquad H_3 = \begin{pmatrix} H^{NN} & H_1^{NN\to DN} & H_2^{NN\to DN} & H_3^{NN\to DN} \\ H_1^{DN\to NN} & H_1^{DN} & 0 & 0 \\ H_2^{DN\to NN} & 0 & H_2^{DN} & 0 \\ H_3^{DN\to NN} & 0 & 0 & H_3^{DN} \end{pmatrix}.$$

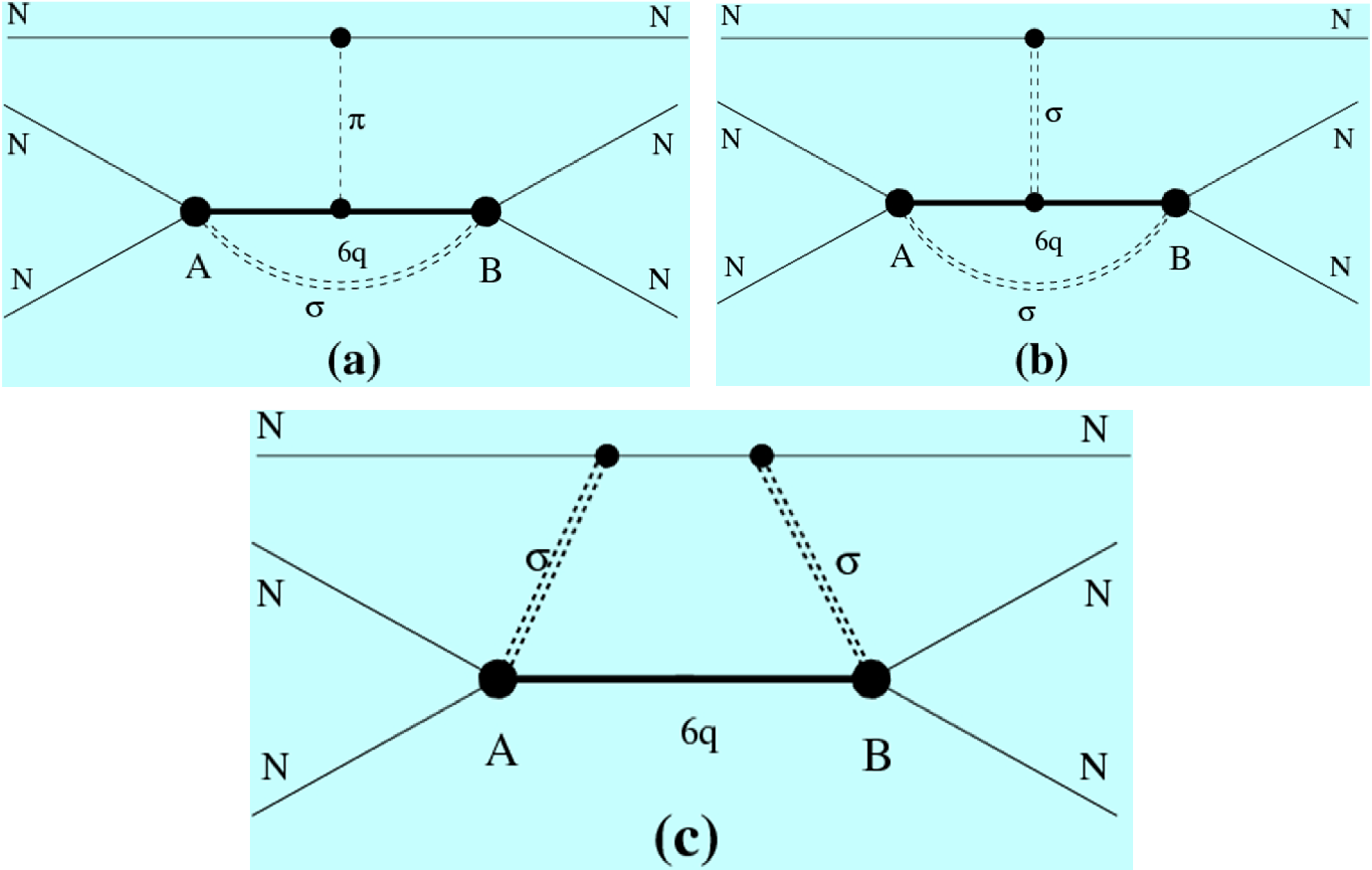
The NN three-body Hamiltonian acts in the external NN space $\mathcal{H}_3^{\rm ex}$ and includes the total kinetic energy T and the sum of external two-body interactions (OPE + TPE): $H_3^{NN} = T + \Sigma_{i<j}\, v_{ij}^{\rm OPE+TPE}$.

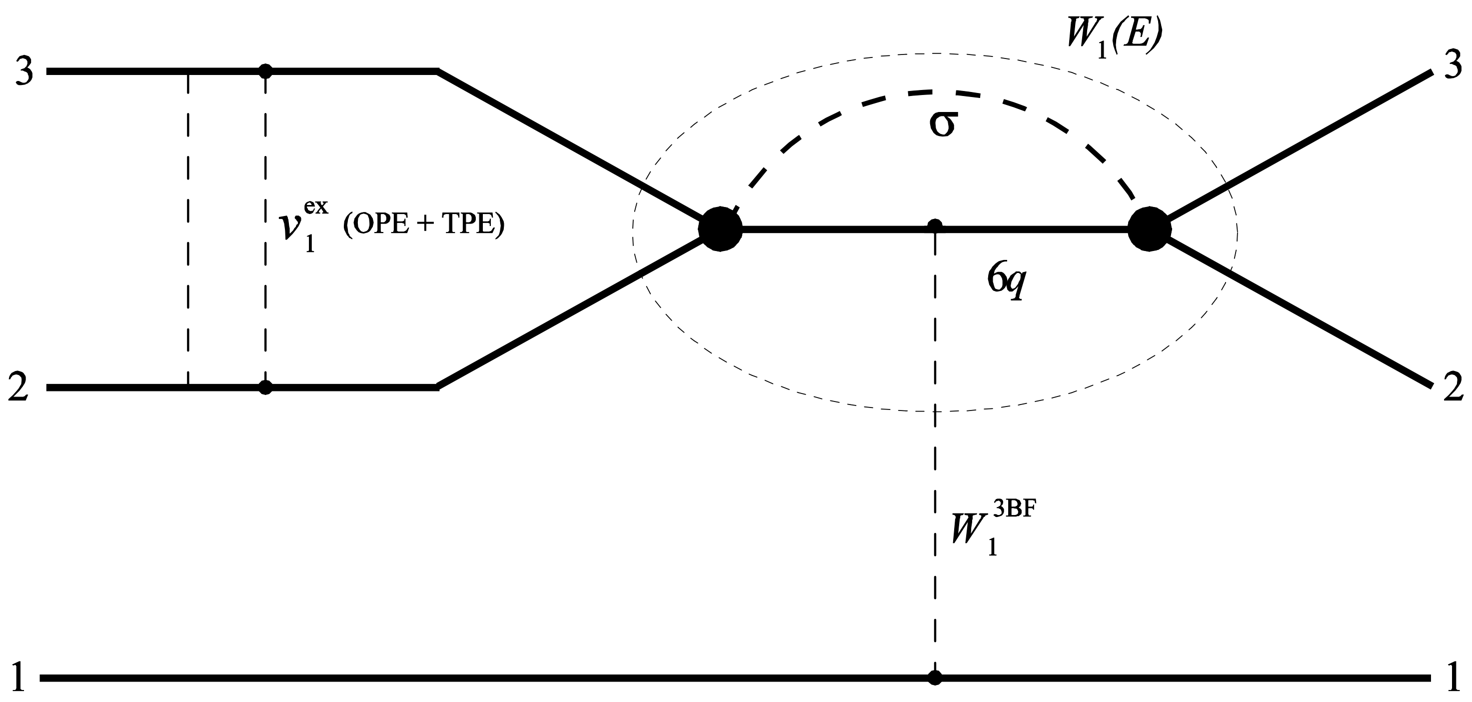
Writing the four-component Schrödinger equation with Hamiltonian H_3: and excluding three dibaryon components, one obtains an effective Schrödinger equation for the NN component of three-body wavefunction $\Psi^{\rm NN}$ with the effective Hamiltonian $H^{\rm eff}(E)$, which in the dibaryon model has a form:

$$H^{\rm eff} = T + \sum_{\alpha}\{V_\alpha^{\rm OPE} + \lambda(E - q^2/(2m))\,|\varphi_\alpha\rangle\langle\varphi_\alpha|\}.$$

But this model leads to appearance of **a new three-body force** in the $3N$ system due to interaction between the dressed bag and third nucleon.

New dibaryon-induced 3*N* force





These three-body forces are expressed (in momentum representation) by integral operators with factorized kernel like:

$$W_\alpha^{3BF}(\mathbf{p}_\alpha, \mathbf{p'}_\alpha, \mathbf{q}_\alpha, \mathbf{q}'_\alpha; E) = \varphi(\mathbf{p}_\alpha)\, w^{3BF}(\mathbf{q}_\alpha, \mathbf{q}'_\alpha; E)\, \varphi(\mathbf{p}'_\alpha),$$

where $\mathbf{p}_\alpha$ is the relative momentum of pair nucleons $(\beta\gamma)$, $\mathbf{q}_\alpha$ is momentum of third nucleon in respect to the pair center of mass, and E is the total three-nucleon energy.

Adding these three-body forces to H^{eff} , we get the total effective Hamiltonian in the NN channel:

$$\boxed{H^{\text{tot}}(E) = H^{\text{eff}}(E) + \sum_\alpha W_\alpha^{3BF}(E)}$$

Results of 3N calculations in dibaryon model with 2- and 3-body forces

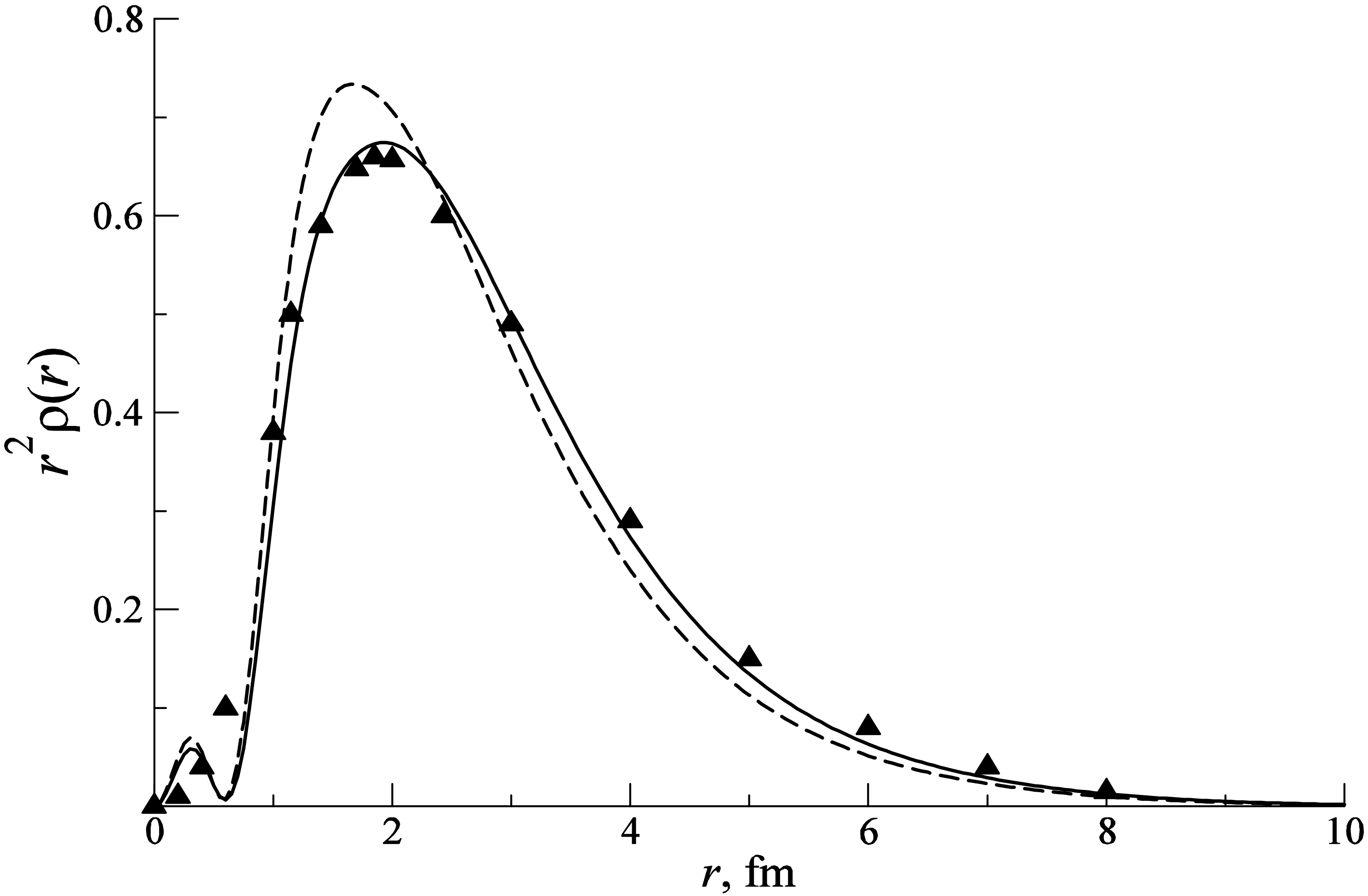
Model	E, MeV	P_D,%	$P_{S'}$,%	P_{6qN},%	Contributions to H, MeV		
					T	$T+V^{(2N)}$	$V^{(3N)}$
			^{3}H				
DBM(I) $g=9.577^{(a)}$	−8.482	6.87	0.67	10.99	112.8	−1.33	−7.15
DBM(II) $g=8.673^{(a)}$	−8.481	7.08	0.68	7.39	112.4	−3.79	−4.69
AV18 + UIX	−8.48	9.3	1.05	–	51.4	−7.27	−1.19
			^{3}He				
DBM(I)	−7.772	6.85	0.74	10.80	110.2	−0.90	−6.88
DBM(II)	−7.789	7.06	0.75	7.26	109.9	−3.28	−4.51
AV18 + UIX	−7.76	9.25	1.24	–	50.6	−6.54	−1.17

a) These values of σNN coupling constant in ^{3}H calculations have been chosen to reproduce the exact binding energy of ^{3}H nucleus. The calculations for ^{3}He have been carried out without any free parameters.

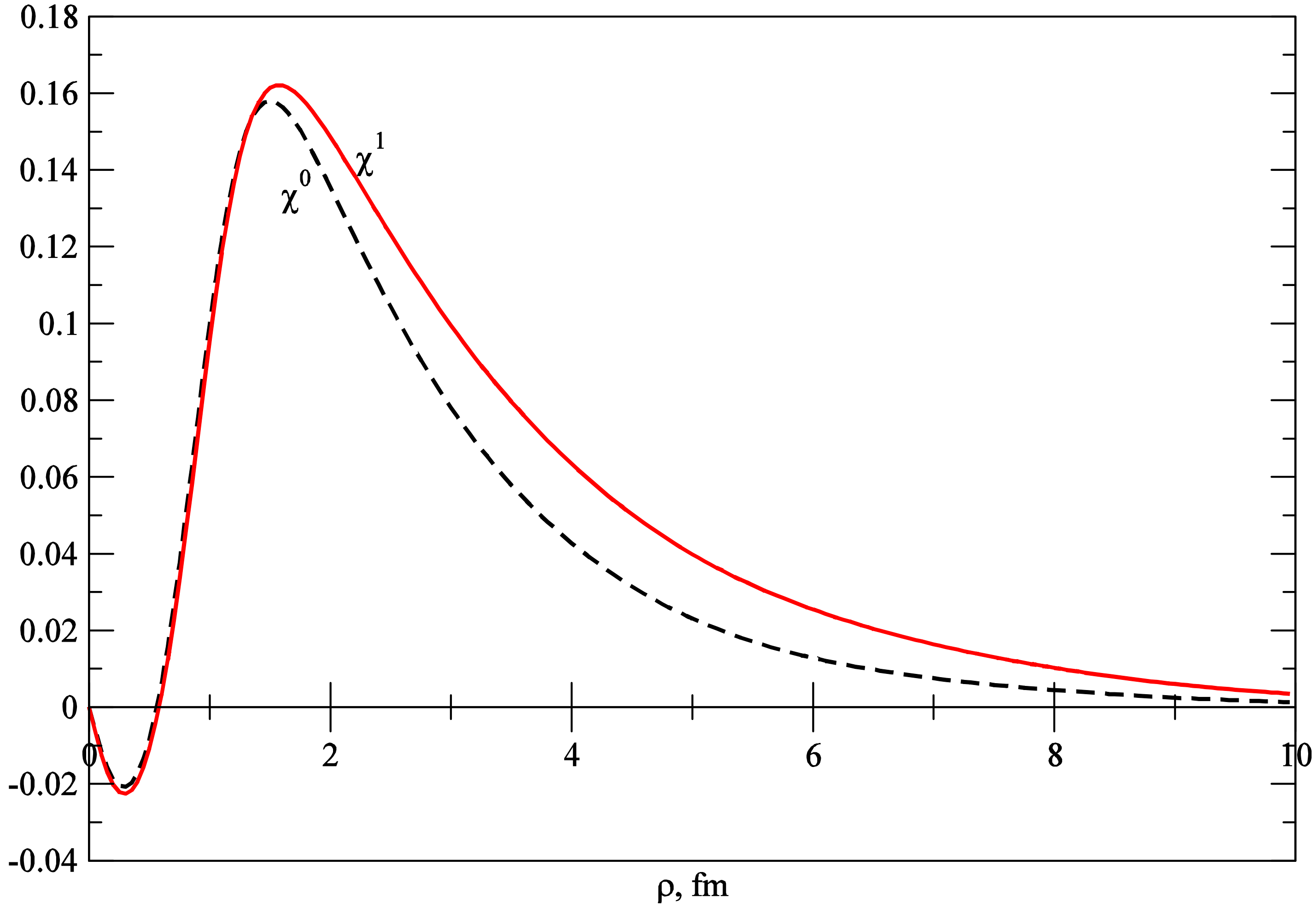
$$\Delta E_{\text{Coul}}^{\text{theor}} = 754 \text{ keV (with no one adjustable parameter)}$$

$$\Delta E_{\text{Coul}}^{\text{exp}} = 764 \text{ keV !}$$

Two-proton density in ^{3}He (solid line) and two-neutron density in ^{3}H (dashed line) for dibaryon model vs. two-proton density in ^{3}He for Bonn *NN* potential (triangles).



Triplet χ^1 and singlet χ^0 components of ^3H wavefunction in dibaryon-nucleon channel

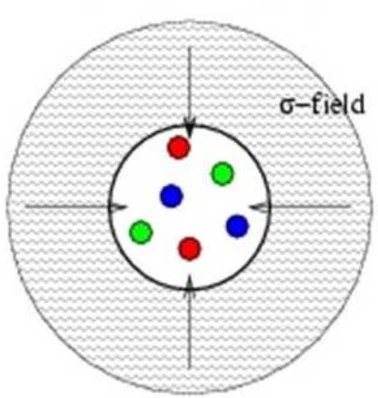


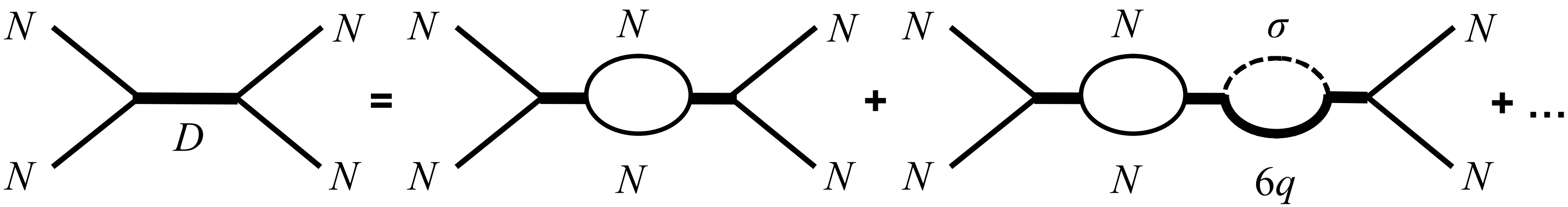
Predictions of dibaryon model for hadron and nuclear physics

Role of the scalar σ-field in dibaryon model

- The dibaryon wave function can be represented as a Fock column:

$$\Psi_D = \begin{bmatrix} \hat{A}(NN\chi_{NN}) \\ \Psi_{\text{bag}}(6q+\sigma) \end{bmatrix}$$



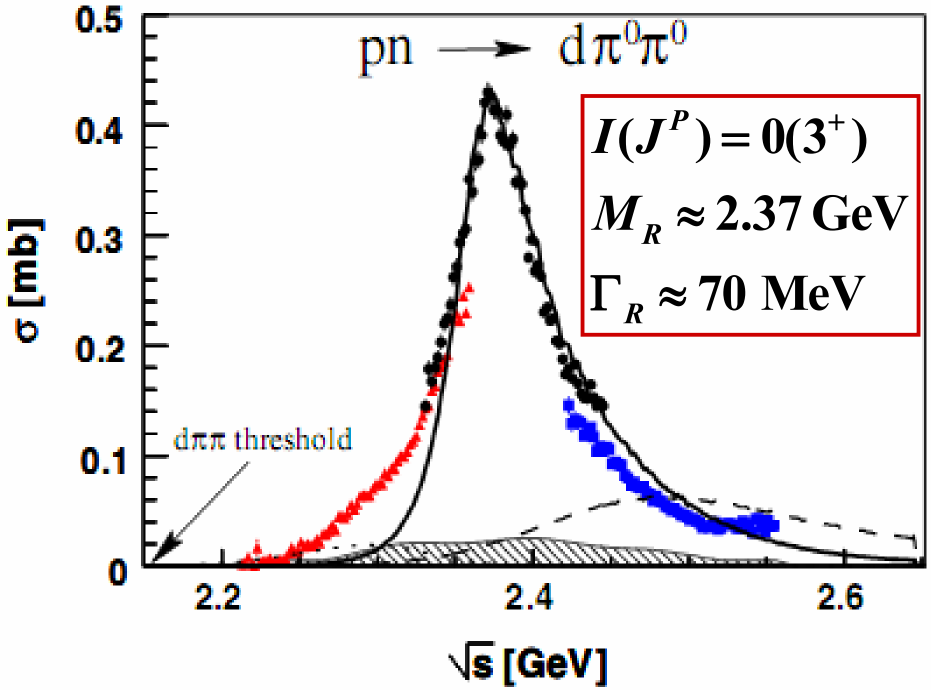


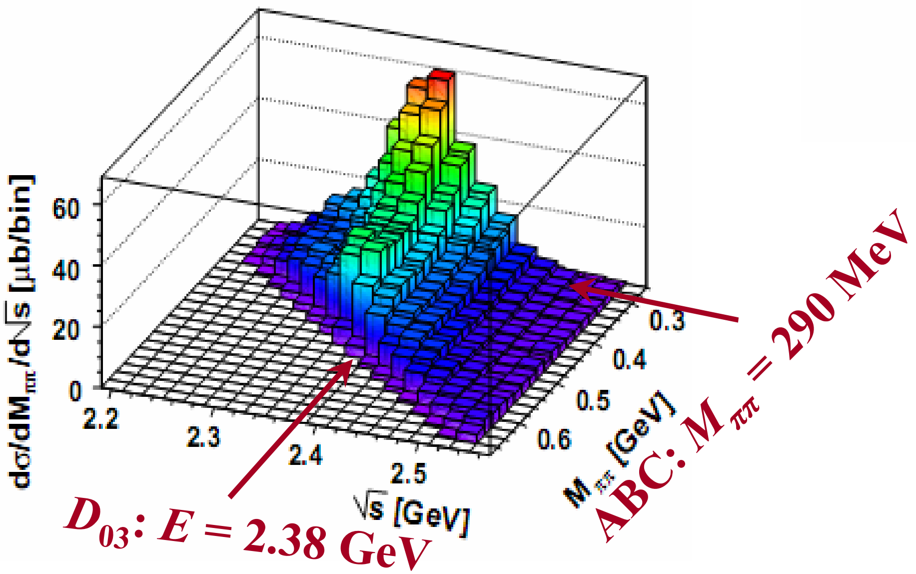
- The scalar σ-field surrounding the 6*q*-bag plays a role of the basic stabilizing factor for the bag. This field pulls all 6 quarks together and thus induces the strong additional attraction in the *NN* channel.
- <u>A question arises</u>: *how to observe this scalar σ-field of the 6q-bag in experiment?*

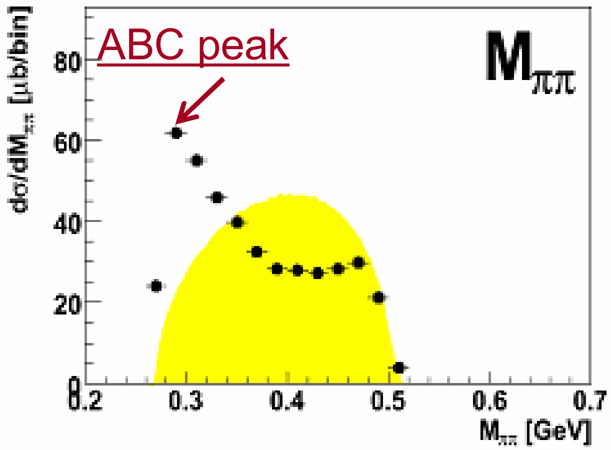
Dibaryon model for the ABC puzzle

The most interesting feature of the recent experiments of the WASA@COSY Collaboration is a clear identification of the old ABC-puzzle with 2π emission from the 0(3⁺) dibaryon state.

[P. Adlarson *et al.*, PRL **106**, 242302 (2011)]







Dibaryon model for the ABC puzzle

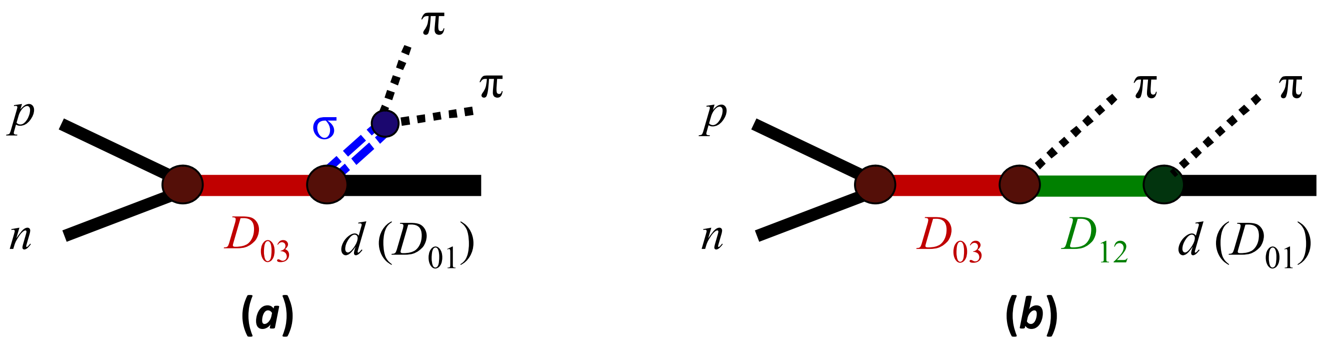
- The ABC puzzle [A. Abashian, N.E. Booth, K.M. Crowe, PRL**5**, 258 (1960)] was a strange enhancement of 2π production very near to the 2π threshold ($2m_\pi \approx 280$ MeV) in scalar-isoscalar channel, i.e., $\pi^0\pi^0$ or $(\pi^+\pi^-)_0$ in p+n, p+d and d+d fusion reactions.
- In the most of theoretical works done for the passed 50 years the puzzle has been explained by the nearby ΔΔ threshold. However, the new WASA@COSY experimental results occurred to be <u>incompatible with such a model</u>.
- So, the experimentalists suggested a new model for the ABC puzzle based on idea of the ΔΔ bound state. Unfortunately, their model includes a non-realistic very soft form factor for ΔΔ bound state and thus looks to be not quite consistent.

Dibaryon model for the ABC puzzle

- The new model for the reaction $pn \to d + (\pi\pi)_0$ at energies $T_p = 1\text{–}1.3$ GeV ($s^{1/2} = 2.32\text{–}2.44$ GeV) includes production of the $D_{03}(2380)$ dibaryon and its subsequent decay into the final deuteron and isoscalar $\pi\pi$ pair via two interfering routes:

  (*a*) emission of $\pi\pi$ pair from a scalar σ meson produced from the meson cloud of the dibaryon;

  (*b*) sequential emission of two pions via an intermediate isovector dibaryon $D_{12}(2150)$.

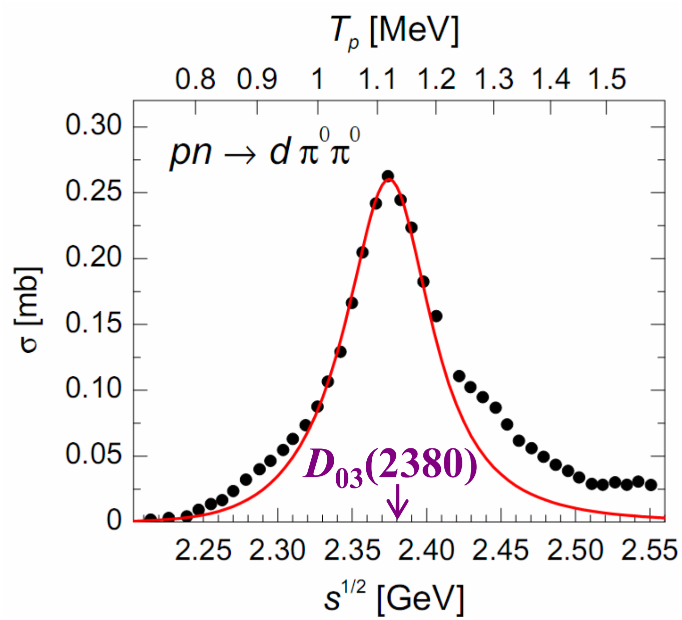


- Transitions between different dibaryon states were considered *for the first time*, similarly to the known transitions between baryons (cf. the Roper resonance decay routes: $N^*(1440) \to N + \sigma \to N + \pi\pi$ and $N^*(1440) \to \Delta(1232) + \pi \to N + \pi\pi$).

[M.N. Platonova, V.I. Kukulin, PRC 87(2013)025202]

Results of the model calculations

I. Total Cross Section



● **Experiment WASA@COSY** [PRL106(2011)242302, renorm. in PLB721(2013)229]

phase space

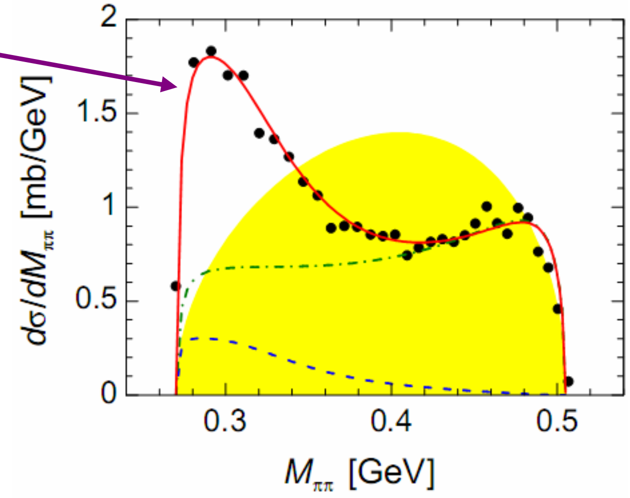
$D_{03} \to d + \sigma$

$D_{03} \to D_{12} + \pi$

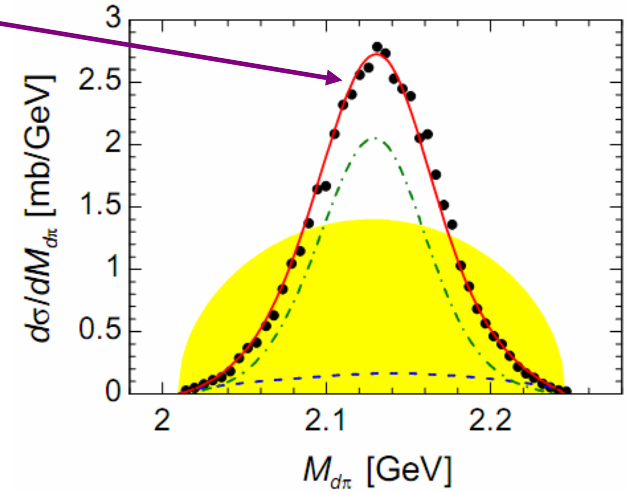
Full calculation

II. Invariant-mass spectra @ $s^{1/2} = 2.38$ GeV

ABC effect (signal of σ meson)



Signal of isovector dibaryon $D_{12}(2150)$



- ✓ **ABC enhancement appears as a consequence of σ meson production**
- ✓ **Peak in $M_{d\pi}$ spectrum reflects production of isovector dibaryon $D_{12}(2150)$**

Experiment on deuteron fragmentation $d + {}^{12}\mathrm{C} \rightarrow p + X$ at $p_d = 8.9$ GeV/c

[V.G. Ableev et al., Nucl. Phys. A393(1983)491]

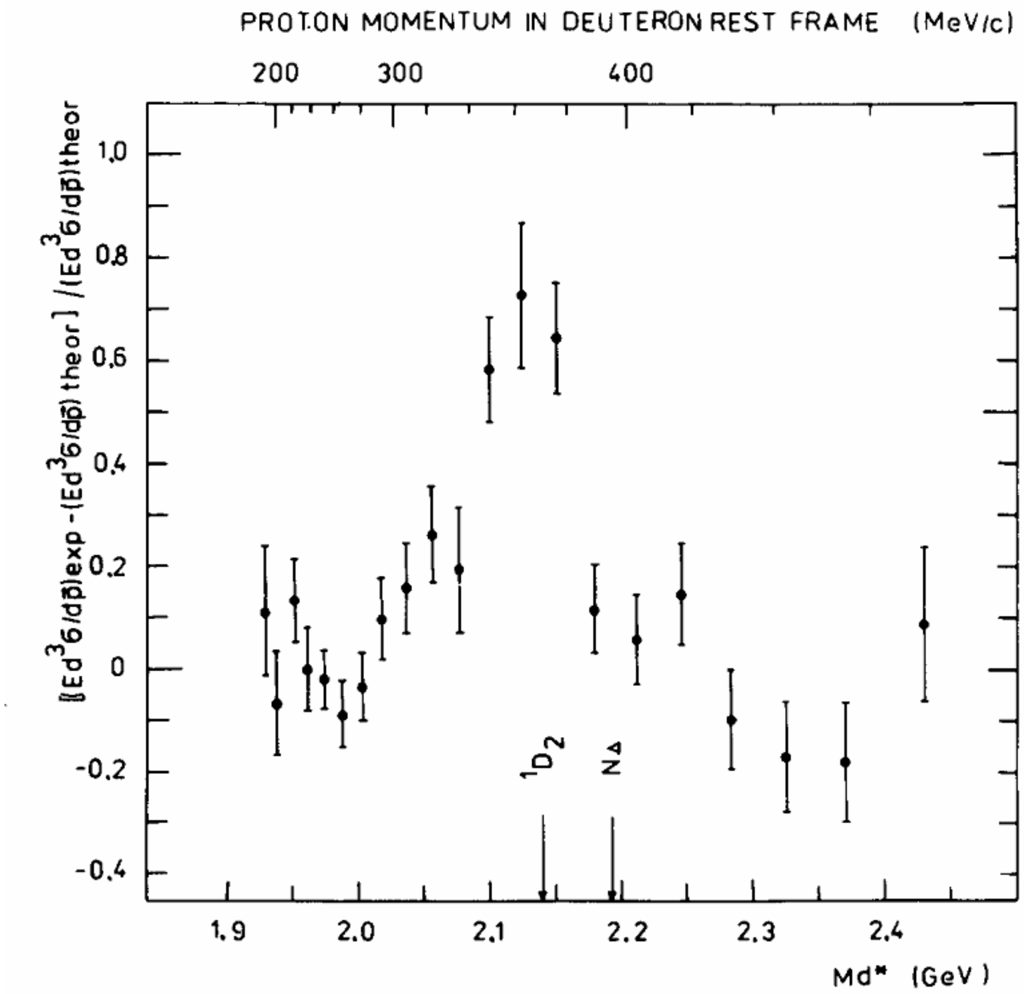


Fig. 3. An enhancement in the region $295 \leq p_{\parallel}^{*} \leq 378$ MeV/c excluded from the fit.

This is a beautiful confirmation of our hypotesa about two-stage decay of the D_{03} resonance.

Dibaryons and the σ-meson puzzle in hadron physics

- The light scalar meson σ (or $f_0(500)$) is the lowest resonance in QCD and one of the most puzzling mesons in the meson Zoo.
- Its role in strong interaction physics is very similar to that of the Higgs boson in electroweak sector (σ meson is responsible for the constituent quark masses and generally for the masses of strongly interacting particles).
- Its mass and width are not constant and depend upon the medium where it appears (chiral symmetry restoration).

Chiral symmetry restoration in dibaryons and in scalar meson sector

- The experimental data in the region of the ABC peak can be fitted very well within the dibaryon model only by taking the σ-meson mass and width which are strongly reduced as compared to their values extracted from ππ dispersion relations [I. Caprini, G. Colangelo, H. Leutwyler, PRL**96**, 132001 (2006)]:

$$\boxed{m_\sigma^{\mathrm{ABC}} \simeq 300\ \mathrm{MeV}, \quad \Gamma_\sigma^{\mathrm{ABC}} \simeq 100\ \mathrm{MeV}}$$

$$\boxed{m_\sigma^{\pi\pi} = 441^{+16}_{-8}\ \mathrm{MeV}, \quad \Gamma_\sigma^{\pi\pi} = 544^{+18}_{-25}\ \mathrm{MeV}}$$

- Such a reduction for the σ-meson parameters means the partial **Chiral Symmetry Restoration (χSR)** effect in the excited (3^+0) dibaryon state.

- The riddle of the σ-meson is interrelated very closely with the χSR phenomenon in QCD.

Chiral symmetry restoration in dibaryons

- χSR effects have been predicted by many authors both in dense (or hot) nuclear matter and even in a single hadron when it gets strongly excited.
- It should be stressed here that the 3^+0 dibaryon with the mass $M(3^+0) \approx 2.38$ GeV is in fact *a strongly excited hadron* (with the excitation energy $E^* \approx 500$ MeV) and the χSR phenomenon is predicted for such states rather reliably.
- Thus, the σ mesons which dress the dibaryon must be much lighter and narrower as compared to the bare σ mesons in ππ scattering in free space.
- So, just this χSR phenomenon is responsible in essence for the basic *NN* attraction at intermediate distances, i.e., for the main component of nuclear force.

- Fully similar χSR effects can be studied also in the Roper resonance state *N**(1440).

In this case the positive parity (2ħω-excited) state *N**(1440) is located well below the lowest negative parity (1ħω-excited) nucleon resonance *N**(1535). It is possible if the *N**(1535) state is on its normal place in the nucleon spectrum while the Roper resonance is <u>strongly shifted downwards</u>.

- Many hadronic models suggested to explain χSR effects in hadronic spectra predict the appearance of parity doublets in nucleonic spectra as a manifestation of χSR phenomenon.

Spin	Chiral multiplet
1/2	$N_+(1440) - N_-(1535)$
1/2	$N_+(1710) - N_-(1650)$
3/2	$N_+(1720) - N_-(1700)$
5/2	$N_+(1680) - N_-(1675)$
7/2	$N_+(?) - N_-(2190)$
9/2	$N_+(2220) - N_-(2250)$
11/2	$N_+(?) - N_-(2600)$

- Thus, the approximate degeneration between the positive and negative parity levels with the same J in nucleon spectrum can be treated as an indicator for the χSR effect.

So, our prediction for the χSR phenomenon in dibaryon states, and thus as a driving QCD mechanism for short-range nuclear force, can help establish a fundamental QCD origin for nuclear physics at all.

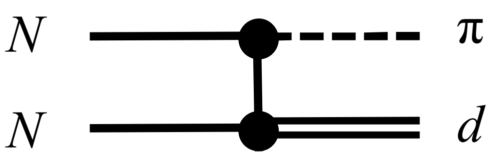
"It is only by the collective analysis of all of these that we can hope to solve the riddle of the σ. It is a puzzle worth solving, since the nature and properties of the σ lie at the heart of the QCD vacuum."

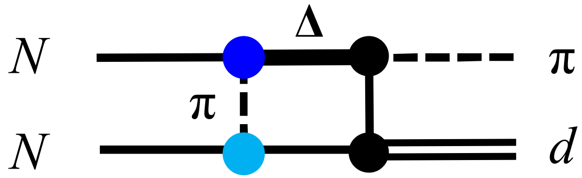
– M.R. Pennington, hep-ph/9905241

Further results for pion production in *NN* collisions

Conventional description for $pp \to d\pi^+$:

ONE (one-nucleon exchange) + $N\Delta$ (N+Δ intermediate state)



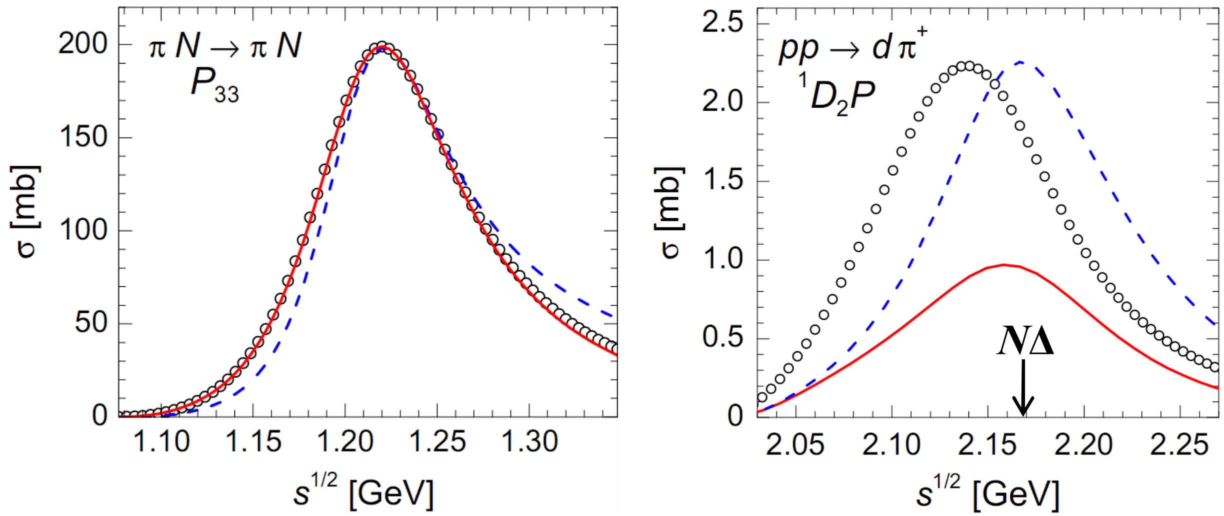


- The basic difficulty is the choice of the short-range cut-off parameters Λ and Λ_* in meson-baryon vertices πNN and $\pi N\Delta$ with a virtual pion.

$$F_{\pi N\Delta} = \frac{f_*}{m_\pi}\frac{p_0^2+\tilde{\Lambda}_*^2}{p^2+\tilde{\Lambda}_*^2}\Bigg|_{(\text{virtual } \pi)} \simeq \frac{f_*}{m_\pi}\frac{m_\pi^2-\Lambda_*{}^2}{w_\pi^2-\Lambda_*{}^2}$$

(p – pion momentum in πN c.m.s.)

$$\Lambda_*{}^2 \simeq \left(\tilde{\Lambda}_*^2 + \left(\frac{M_\Delta^2-m^2}{2M_\Delta}\right)^2\right) \Big/ \left(\frac{M_\Delta^2+m^2}{2M_\Delta^2}\right)$$



○ PWA (SAID)

— $\tilde{\Lambda}_* = 0.3\,\text{GeV}$ ($\Lambda_* = 0.44\,\text{GeV}$)

- - $\tilde{\Lambda}_* = 0.55\,\text{GeV}$ ($\Lambda_* = 0.7\,\text{GeV}$)

- Cut-off parameters describing precisely the πN elastic scattering ➡ conventional mechanisms (ONE+$N\Delta$) give only a half the partial (^1D_2P) $pp \to d\pi^+$ cross section
- Enhancing the $\pi N\Delta$ cut-off value *ad hoc* ➡ the magnitude of the $pp \to d\pi^+$ cross section can be reproduced but with a substantial energy shift
- *An alternative way:* taking the intermediate dibaryon resonances in the NN channels $^1D_2$, $^3F_3$, $^1G_4$, etc., into account

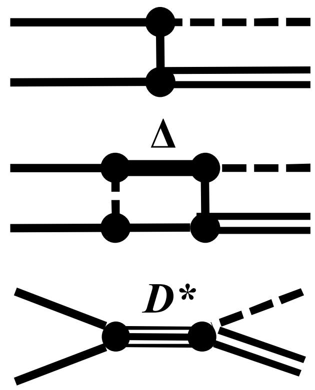
Extended model for $pp \to d\pi^+$:

[M.N. Platonova, V.I. Kukulin, nucl-th/1412.4574]

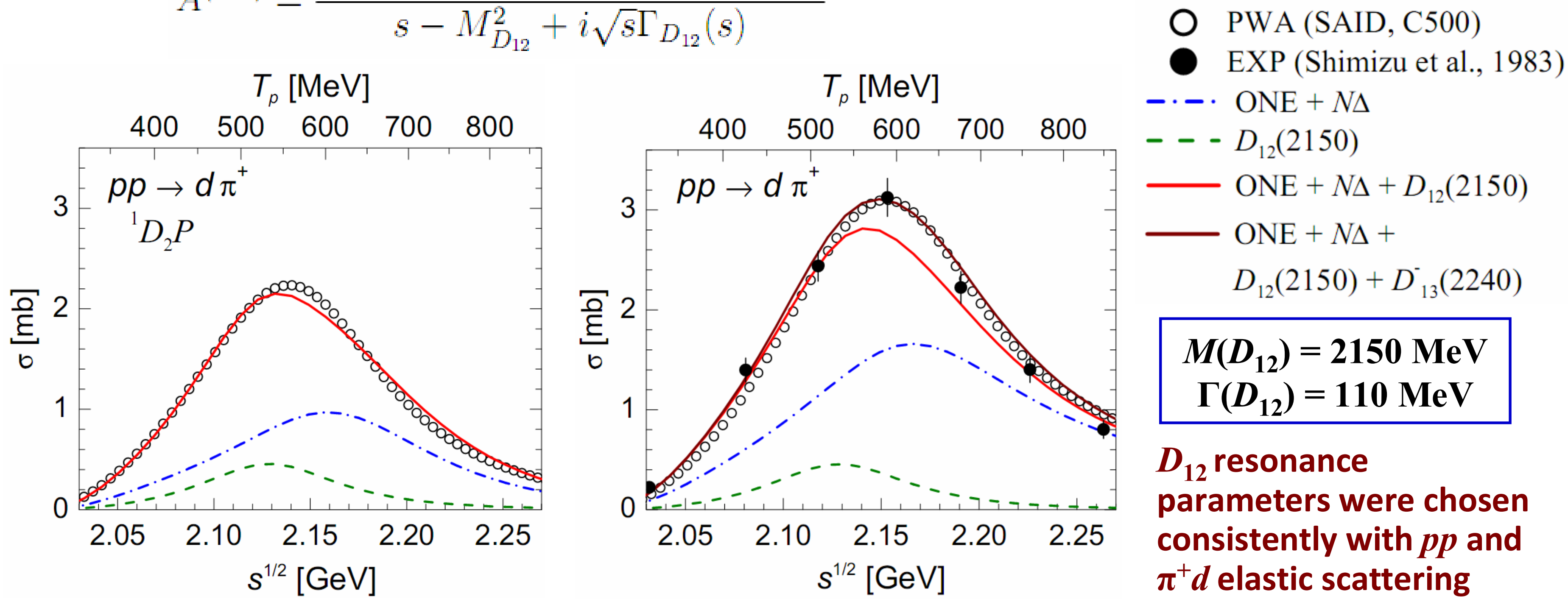
ONE **(one-nucleon exchange)**

+ $N\Delta$ (N+Δ intermediate state)

+ D^* (dibaryon resonances)



$$A^{(D_{12})} = \frac{16\pi s\sqrt{2\Gamma_{D_{12}\to pp}(s)\Gamma_{D_{12}\to\pi d}(s)/pq}}{s - M^2_{D_{12}} + i\sqrt{s}\Gamma_{D_{12}}(s)}$$

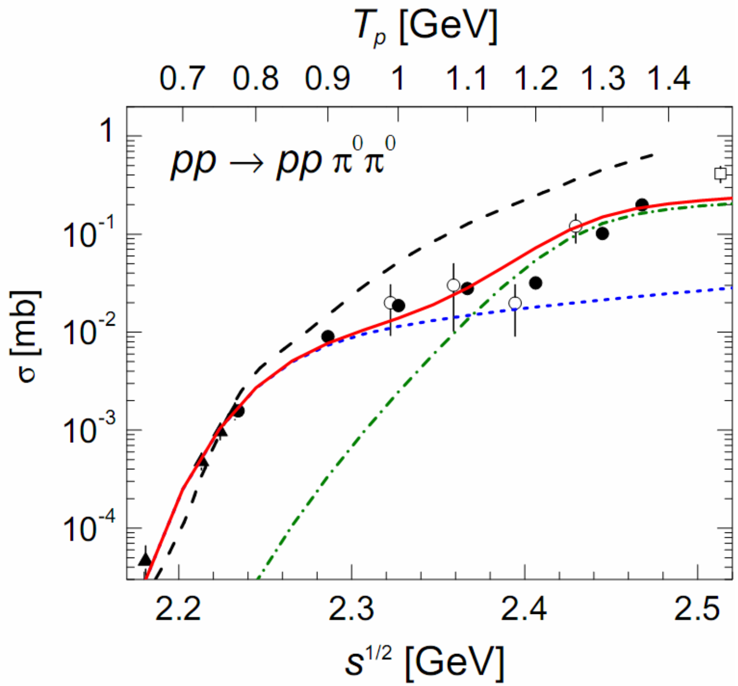


$M(D_{12})$ = 2150 MeV
$\Gamma(D_{12})$ = 110 MeV

D_{12} resonance parameters were chosen consistently with pp and π^+d elastic scattering

- Inclusion of dibaryon resonances improves the description of experimental data without *ad hoc* adjustment of cut-off parameters.
- Accurate description of the total cross section in a broad energy range requires two dibaryon resonances: $D_{12}(2150)$ [$^1D_2$] and $D^-_{13}(2240)$ [$^3F_3$].

Isovector dibaryon signals in reaction $pp \to pp + \pi^0\pi^0$



Conventional model (E. Oset et al., 1998):

$$NN^*(1440) + \Delta\Delta \quad (\Lambda_* \simeq 1.3\ \mathrm{GeV!})$$

Alternative (dibaryon) model:

$$D_{13}^{-}(2240)\,[^3F_3] + D_{14}(2430)\,[^1G_4]$$

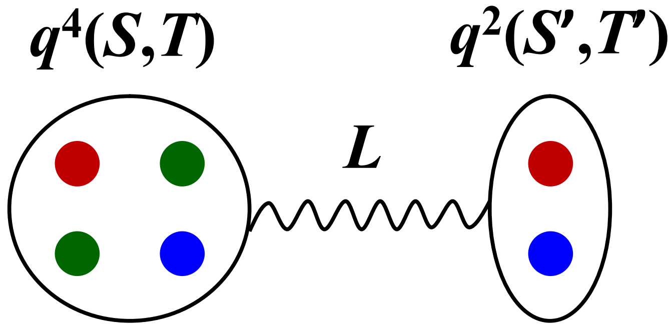
$$\sigma = \sum_{J=3,4} \frac{\pi(2J+1)}{p^2} \frac{s\Gamma_{D_J}^{(i)}(s)\Gamma_{D_J}^{(f)}(s)}{(s - M_{D_J}^2)^2 + s\Gamma_{D_J}(s)^2}$$

- **Thus, taking into account the intermediate dibaryon resonances allows to describe not only phase shifts for elastic NN scattering, but also inelastic processes in NN collisions accompanied by one- and two-meson production.**

Dibaryon Spectroscopy

- **Nijmegen & ITEP model**
  [P. Mulders et al., PRD21(1980)2653;
  L. Kondratyuk et al., Sov.J.Nucl.Phys.45(1987)776]

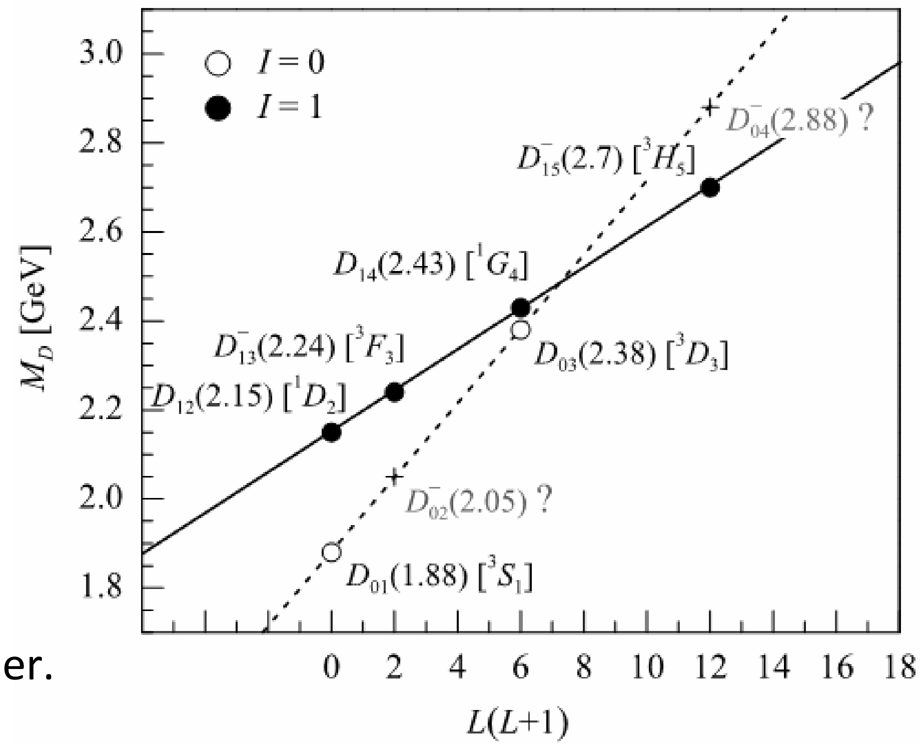
  Dibaryons as orbital excitations
  of two-cluster system q^4-q^2;
  Regge trajectory on (J,M^2)



- For the lowest states $(\Delta M \ll M_0)$:
  non-relativistic rigid-rotor model

$$M(L) \simeq M_0 + \frac{\hbar^2}{2\mathcal{I}} L(L+1)$$

  Almost straight line on $(L(L+1),M)$!



- Tetraquark q^4 (S=1,T=0);
  Diquark q^2:
  scalar (S′=T′=0) for I=0 dibaryons,
  axial (S′=T′=1) for I=1 dibaryons

  Each I=1 dibaryon should have an I=0 partner.

  Are there additional I=0 states? Are there another dibaryon trajectories?

  More questions to be answered…

Conclusions

1. The dibaryon mechanism based, in essence, on the χSR phenomenon is likely to be responsible for short-range nuclear force.
2. We derived a potential model (both in non-relativistic and relativistic formulations) based mainly symmetry considerations of a $6q$ system, which describes the empirical *NN* phase shifts reasonably well in a wide energy range 0–1000 MeV. (From the model we can also derive the imaginary parts of phase shifts related to single and double pion emission.)
3. We tested the model successfully in $3N$ calculations (for ^{3}He and ^{3}H bound states).

Conclusions

4. The dibaryon model predicts:

- very strong 3*N* force (with central and spin-orbit components) in all nuclei induced by the scalar σ-meson exchange;
- transitions between various dibaryon states, e.g., $^1D_2 \leftrightarrow {}^3S_1$(deuteron) $+ \pi(l_\pi{=}1)$, $^3D_3 \leftrightarrow {}^1D_2 + \pi(l_\pi{=}1)$, etc.;
- a novel EOS in dense nuclear matter (e.g., in neutron stars) and in collisions of heavy ions;
- phase transition in cold nuclear matter to superdense state which can be a good candidate for **dark matter**!

Physics Letters B

Volume 391, Issues 3–4, 16 January 1997, Pages 255–260

Nuclear matter with a Bose condensate of dibaryons in relativistic mean-field theory

Amand Faessler[a], A.J. Buchmann[a], M.I. Krivoruchenko[a, b], B.V. Martemyanov[b]

If sufficiently light dibaryon resonances exist, a Bose condensate of dibaryons can occur in nuclear matter before the quark-hadron phase transition. Within a relativistic mean-field model we show that heterophase nuclear-dibaryon matter is for a wide set of parameters energetically more favorable than normal nuclear matter. Production of dibaryons is, however, relatively suppressed as compared to estimates based on the model of non-interacting nucleons and dibaryons.

PHYSICAL REVIEW C VOLUME 57, NUMBER 3 MARCH 1998

Nuclear matter with a Bose condensate of dibaryons in a relativistic Hartree approximation

Amand Faessler,[1] A. J. Buchmann,[1] and M. I. Krivoruchenko[1,2]
[1] Institut für Theoretische Physik, Universität Tübingen, Auf der Morgenstelle 14, D-72076 Tübingen, Germany
[2] Institute for Theoretical and Experimental Physics, B.Cheremushkinskaya 25, 117259 Moscow, Russia
(Received 5 November 1997)

The Green's functions are constructed and a one-loop calculation is given for the scalar and vector densities and for the equation of state of nuclear matter with a Bose condensate of dibaryons. This is the lowest approximation in the loop expansion of quantum hadrodynamics, sufficient to account for the presence of dibaryons not in the condensate in the heterophase nucleon-dibaryon matter. It leads to a finite effective nucleon mass and remains consistent with increasing the density. [S0556-2813(98)03003-9]

Progress of Theoretical Physics, Vol. 95, No. 4, April 1996

Dibaryon Condensation and the Compressible Bag Model

Shigenori KAGIYAMA, Akira MINAKA* and Akihiro NAKAMURA

Department of Physics, College of Liberal Arts, Kagoshima University, Kagoshima 890
**Department of Physics, Faculty of Education, Kagoshima University, Kagoshima 890*

(Received August 14, 1995)

The compressible bag model of hadronic matter, including baryons and dibaryons, is formulated at finite temperature, and the phase structure of the matter is investigated in the model. It is shown that, for most cases, dibaryons are found in the condensed phase. The effect of the condensation on experimental data is discussed.

International Journal of Theoretical Physics, Vol. 42, No. 6, June 2003 (© 2003)

A Stable H-Dibaryon: Dark Matter Candidate Within QCD?

Glennys R. Farrar[1]

Received April 14, 2003

Particle physics arguments suggest that the H-dibaryon—a state consisting of two u, two d, and two s quarks—may have a mass $\approx 1.5 \pm 0.2$ MeV, and that $r_{\mathrm{H}} \lesssim \frac{1}{4} r_{\mathrm{N}}$. Remarkably, the observed stability of nuclei and other experimental limits do not exclude this scenario at present, as discussed here. If they are present in sufficient abundance, relic H's would be the cold dark matter. Tests of this scenario are discussed.

Moscow – Tübingen group:

V.I. Kukulin
I.T. Obukhovsky
M.N. Platonova
V.N. Pomerantsev
O.A. Rubtsova
M.A. Shikhalev

A. Faessler
P. Grabmayr
M. Kaskulov

References

1. *Arguments against OBE models of nuclear force and new mechanism for intermediate- and short-range nucleon-nucleon interaction.* // Phys. At. Nucl. **64**, 1667 (2001).
2. *Dressed six-quark bags at short and intermediate NN ranges.* // Nucl. Phys. **A689**, 327c (2001).
3. *The new mechanism for intermediate- and short-range nucleon-nucleon interaction.* J. Phys. G **27**, 1851 (2001).
4. *Two-component dressed-bag model for NN interaction: deuteron structure and phase shifts up to 1 GeV.* // Int. J. Mod. Phys. E **11**, 1 (2002).
5. *A six-quark dressed bag description of np → dγ radiative capture.* // Int. J. Mod. Phys. E **12**, 449 (2003).

References

6. *The properties of the three-nucleon system with the dressed-bag model for NN interaction: I. New scalar three-body force.* // J. Phys. G **30**, 287 (2004).
7. *The properties of the three-nucleon system within the dressed-bag model for 2N and 3N forces: II. Coulomb and CSB effects.* // J. Phys. G **30**, 287 (2004).
8. *Dibaryon model for nuclear force and the properties of the 3N system.* // Phys. At. Nucl. **68**, 1453 (2005).
9. *Description of intermediate- and short-range NN nuclear force within a covariant effective field theory.* // Ann. Phys. (NY) **320**, 71 (2005).
10. *Isoscalar short-range current in the deuteron induced by an intermediate dibaryon.* // Phys. Rev. C **74**, 064005 (2006).
11. *Photon-induced neutron polarization from the 2H(γ,n)1H reaction within the NN-force model with an intermediate dibaryon.* // Phys. Rev. C **77**, 041001(R) (2008).
12. *Dibaryon concept for nuclear force and its experimental evidence.* // Phys. At. Nucl. **72**, 1786 (2009).
13. *Experimental and theoretical indications for an intermediate σ-dressed dibaryon in the NN interaction.* // Ann. Phys. **325**, 1173 (2010).
14. *Di- and multibaryon clusters in nuclei: A nontraditional view on the nature of nuclear forces and on the structure of nuclei.* // Phys. At. Nucl. **74**, 1567 (2011).
15. *ABC effect as a signal of chiral symmetry restoration in hadronic collisions.* // Phys. Rev. C **87**, 025202 (2013).
16. *Short-range components of nuclear force: experiment versus mythology.* // Phys. At. Nucl. **76** (2013).

Thank You
For Your Attention!