Critical survey of modern concepts for nuclear force

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Content

1. Meson-exchange concept of nuclear force: why the modern NN potentials are so complicated?
2. Nucleon momentum distribution: experiment vs. theory.
3. Cumulative nuclear phenomena: they require very short-range nucleon clustering (fusion).
4. Experimental evidence for dibaryon production
5. Dibaryon origin of basic nuclear force.
Motivation of the survey

1. Modern approaches for the nuclear force models do not provide the consistent description of very numerous data in NN, Nd, dd etc. collisions.

2. There are many new phenomena in nuclear physics where we cannot even imagine how to implement the modern concept of nuclear force based on meson exchange mechanism.

3. It is well recognized by everybody now that nuclear physics should be based on Quantum Chromodynamics (QCD). But how to do it? And what is the bridge between fundamental QCD and nuclear physics?
Nuclear Force: early stage
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

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.

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.
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.
There is another fundamental difficulty:

we cannot observe any regular behavior neither in NN potentials nor in NN phase shifts.
Figure 2-34  The figure illustrates the phase parameters for nucleon-nucleon scattering in the channels with \( L \leq 2 \). The low-energy behavior is determined by the effective range parameters (2-183); the data for \( E > 24 \text{ MeV} \) are taken from the analysis by R. A. Arndt and M. H. MacGregor, *Phys. Rev.* **141**, 873 (1966); similar analyses have been given by Breit et al. (1962), Hull et al. (1962), and, more recently, by MacGregor et al. (1968). The definition of the phase parameters in terms of the scattering matrix is given by Eq. (2-222).
NN phase shifts

(Fig. from A. Bohr, B. Mottelson, Nuclear Structure, Vol. I)
NN potentials

(Fig. from A. Bohr, B. Mottelson, Nuclear Structure, Vol. I)
**NN potentials**

**Figure 2-35** The phenomenological nucleon-nucleon potentials shown in the figure are taken from the analysis of T. Hamada and I. D. Johnston, *Nuclear Phys.* 34, 382 (1962); similar potentials have been obtained by Lassila et al. (1962). The dotted potentials (OPEP) correspond to the one-pion exchange potential (Eq. (2-190)). For an example of a soft-core potential, see Reid (1968), and for a nonlocal potential, see Tabakin (1964).

(Fig. from A. Bohr, B. Mottelson, Nuclear Structure, Vol. I )
In this respect the nuclear force does not resemble any other force in Nature!

While the Yukawa mechanism gave a correct picture for the long-range nuclear force through a $\pi$-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 $p_m > 200 – 300 \text{ MeV/c}$, 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 $^3\text{He}$. 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 $^3\text{He}(e,e'\text{pp})$, $^3\text{He}(e,e'\text{pn})$, etc., at missing momenta $p_m > 300$ MeV/c.

The averaged $^3\text{He}(e,e'\text{pp})$ 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 $2N$ currents are based on full Faddeev $3N$ calculations with three-nucleon force.

The $^3\text{He}(e,e'\text{pn})$ 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.
• At nucleon momenta in $^3$He above $k_{\text{max}} \approx 250$ MeV/c the experimental cross sections are considerably larger than predictions of theoretical models which make use of the traditional $NN$ and $3N$ forces. The same story we observe in $^4$He, etc.

• On the other hand, one can analyze the level of agreement between the traditional $2N$ and $3N$ 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 $^9$Be elastic scattering. Solid line – nonrelativistic Faddeev calculation using AV18 potential. Other lines – some relativistic effects added [H.Witala et al., PRC 71, 054001 (2005)]

Proton analyzing power in pd elastic scattering
Differential cross sections integrated over the CLAS acceptance 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!

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.
• 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 \(^3\text{He}\)(e,e’pp), \(^3\text{He}\)(e,e’pn), etc., demonstrates this very clearly (3N final state rescatterings have been included in theoretical calculations).
The similar difficulty is observed also in the nucleon momentum distribution in inter-nuclear collisions (in all such collisions one observes a large deficit of the high-momentum components).
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.
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.
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

\[ p \geq 300 \text{ MeV}/c \]

Figure 1.1: Kinematics of backward emitted nucleons.
First experiments: JINR, 1950 - 1970s

- First experiments by the group of M.G. Mescheryakov at the JINR Synchrocyclotron with 660-MeV proton beam: knock-out of fast deuterons from nuclei A(p,pd) [L.S. Azhgirey et al., JETP 33, 1185 (1957); G.A. Leksin et al., JETP 32, 445 (1957)]: **observation of a large excess of fast deuterons compared to the evaporation model.**

“It looks like a flying bullet is reflected from the window glass”
- M.G. Mescheryakov.

For these pioneering results, **JINR received its first discovery diploma** [L.S. Azhgirey et al., Diploma No. 221, July 1, 1957].


- These experiments were continued and extended in 1960-1980s by G.A. Leksin et al. at ITEP 8-GeV accelerator and led (together with experiments of Frankel et al. in USA) to a discovery of **nuclear scaling and superscaling phenomena.**
Experiments on cumulative particles production in high-energy collisions
(by G.A. Leksin et al., ITEP)

Scattering of fast particles off nuclei at large angles in lab. system

Dependence of invariant function of cumulative neutrons (proportional to neutron yield) on the neutron kinetic energy for backward emitted neutrons:
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 ($\pi^-$, $\pi^+$, $K^-$, $K^+$, etc.) on value of $\alpha$ (effective mass of multibaryons in target nucleus which participate in the process).
All these experimental data do require an enhanced high-momentum components of nuclear wave functions!

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

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

- 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 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 $\pi NN$, $\pi N\Delta$, $\rho NN$, etc., vertices.

• In fact, in OBE-like models one chooses usually these cut-off parameters $\Lambda \sim 1.2 - 1.5$ GeV/$c$.
Such values of $\Lambda$’s correspond to a very short radius ($r \sim 0.15$ fm!) of the $\pi N$, $\rho N$, etc., interactions which contradicts to both fundamental QCD-based approaches and experimental data. So, such very high $\Lambda$-values imitate somehow the strong short-range interaction, especially of tensor nature.
Modern experimental status of dibaryons
Theoretical prediction of 6 zero-strangeness low-lying dibaryons on the basis of SU(6) symmetry F.J. Dyson and N.-H. Xuong, PRL 13, 815 (1964):

Table I. \( Y = 2 \) states with zero strangeness predicted by the 490 multiplet.

<table>
<thead>
<tr>
<th>Particle</th>
<th>( T )</th>
<th>( J )</th>
<th>SU(3) multiplet</th>
<th>Comment</th>
<th>Predicted mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_{01} )</td>
<td>0</td>
<td>1</td>
<td>10*</td>
<td>Deuteron</td>
<td>( A )</td>
</tr>
<tr>
<td>( D_{10} )</td>
<td>1</td>
<td>0</td>
<td>27</td>
<td>Deuteron singlet state</td>
<td>( A )</td>
</tr>
<tr>
<td>( D_{12} )</td>
<td>1</td>
<td>2</td>
<td>27</td>
<td>S-wave ( N-N^* ) resonance</td>
<td>( A + 6B )</td>
</tr>
<tr>
<td>( D_{21} )</td>
<td>2</td>
<td>1</td>
<td>35</td>
<td>Charge-3 resonance</td>
<td>( A + 6B )</td>
</tr>
<tr>
<td>( D_{03} )</td>
<td>0</td>
<td>3</td>
<td>10*</td>
<td>S-wave ( N^<em>-N^</em> ) resonance</td>
<td>( A + 10B )</td>
</tr>
<tr>
<td>( D_{30} )</td>
<td>3</td>
<td>0</td>
<td>28</td>
<td>Charge-4 resonance</td>
<td>( A + 10B )</td>
</tr>
</tbody>
</table>

- 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 \( N-\Delta \) and \( \Delta-\Delta \) 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 $pp \rightarrow pp$, $\pi^+d \rightarrow \pi^+d$ and $\pi^+d \rightarrow pp$ (by N. Hoshizaki et al., and others) revealed the series of isovector resonances in $NN$ channels $^1D_2$, $^3F_3$, $^1G_4$, etc.
- The lowest ($^1D_2$) isovector resonance: $I(\ell^P) = 1(2^+)$, $M \approx 2140–2160$ 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 $\pi^+d \rightarrow pp$ total cross section

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

- 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 $2\pi$-production reactions in $p+n$, $p+d$ and $d+d$ collisions at intermediate energies ($E \sim 0.7–1.7$ GeV).

- They found an **unambiguous dibaryon resonance signal** in $p+n$ collisions at $T_p \sim 1–1.4$ GeV in $2\pi$-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 $\Delta\Delta$ threshold and can be treated in a model of $\Delta\Delta$ near-threshold bound state.
Evidence for $D_{03}$ dibaryon from $n+p$ elastic scattering

Evidence for a New Resonance from Polarized Neutron-Proton Scattering

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

CERN Courier July/August 2014

News

New Particles

COSY confirms existence of six-quark states

$D_{03} \approx \Delta\Delta(30\%) + C\bar{C}(70\%)$  

[F. Huang et al., nucl-th/1505.05395; 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 $\Gamma(D_{03}) = 70–90$ MeV $\ll 2\Gamma(\Delta) = 235$ 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!

$\langle \sqrt{s} \rangle_{\text{pole}} = 2380 \pm 10 - i40 \pm 5$ MeV
Additional confirmation of \(D_{12}\) and \(D_{03}\) resonances

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

\[
M(D_{12}) = 2151 \pm 2 \text{ MeV}, \quad \Gamma(D_{12}) = 120 \pm 6 \text{ MeV}
\]

\[
M(D_{03}) = 2363 \pm 20 \text{ MeV}, \quad \Gamma(D_{03}) = 65 \pm 17 \text{ MeV}
\]


- Very good agreement with Dyson and Xuong predictions as well as with experimental findings!
New experiments of the COSY/ANKE Collaboration

\[ pp \rightarrow \{ pp \}_s \pi^0 \]

Observation of isovector dibaryon resonance-like states with a mass of 2.2 GeV/c²

- Two main transitions \( ^3P_0 \rightarrow ^1S_0 s, \, ^3P_2 \rightarrow ^1S_0 d \)
- \( \{ d\sigma_0/d\Omega, \, \kappa, \, A_y^{\text{max}} \} \rightarrow \{ |M^P_s|, \, |M^P_d|, \, \phi \} \)

Partial wave energy dependence

- \(^3P_2\) resonance parameters:
  \[ E_R = 2195 \pm 8 \text{ MeV} / c^2, \quad \Gamma = 134 \pm 22 \text{ MeV} / c^2 \]
  with \( \chi^2 / \text{ndf} = 8 / 6 \)

- Indication on resonant behaviour in \(^3P_0 s\), parameters:
  \[ E_R = 2199 \pm 5 \text{ MeV} / c^2, \quad \Gamma = 94 \pm 11 \text{ MeV} / c^2, \]
  \( c_{bg} = 2.4 \pm 0.2 \mu b / \text{sr} \)
  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 (e.g. the ansatz of Jastrow).

• 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 $\chi/\Lambda$ ($\Lambda \sim 1$ 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 some basic short-range effects (subthreshold meson production, cumulative processes, high ratio of pn to pp correlations in nuclei, etc.)

Thus, many basic experiments on short-range correlations in nuclei do not agree to the conventional theories of nuclear forces.
Why dibaryons?
Qualitative picture

• The short-range $NN$ interaction (at $r_{NN} < 1$ fm) occurs in the area where two nucleons get overlapped because $<r_{Nq}^> \sim 0.6$ 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.

(It will be shown in the talk how to replace such a repulsive core by non-local repulsive mechanism fully compatible with the quark model.)
Why 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 $\sigma$-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 $\sigma$-meson exchange between quarks taking into account the loops: $\sigma \rightarrow \pi\pi\rightarrow\sigma\ldots$, i.e., the $\sigma$-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, ANKE@COSY, Mainz, etc.) we should change all the traditional conception for the short-range forces in $2N$ and $3N$ sectors.
The dibaryon mechanism for $NN$ interaction
As a result of recent great progress in finding dibaryon resonances in numerous nuclear and hadronic processes one should consider a possible role of these resonances in basic NN interaction, in combination with a simple meson exchange.

One can imagine a crucial importance of intermediate dibaryons not only in NN but also in NΔ and ΔΔ channels at low and intermediate energies.
The simplest case: two-channel model with one external and one inner channel which gives a complex pole in effective interaction in external channel.

Formulation of the model:
The total matrix Hamiltonian for such a two-channel problem has the form:

\[
H = \begin{pmatrix} h_{NN} & \lambda_1 |\phi\rangle \langle \alpha| \\ \lambda_1 |\alpha\rangle \langle \phi| & E_D |\alpha\rangle \langle \alpha| \end{pmatrix},
\]

where the external-channel Hamiltonian \( h_{NN} \) acts in the space of \( NN \) variables and includes the peripheral \( NN \) interaction which is exhausted by the one-pion exchange potential (OPEP). In case of the single-pole model, the Hilbert space of the inner channel is one-dimensional and therefore the inner Hamiltonian is reduced to a single term with a complex eigenvalue \( E_D = E_0 - i\Gamma/2 \).
The form factor $\phi$ of the transition between the $NN$ and the inner (dibaryon) channels can be derived from a quark microscopic model for the dibaryon state or found from the fit within some ansatz. In our case (using a conventional model for six-quark bag with h.o. confining potential)

$$\phi(r) = N r^{l+1} \exp \left[ -\frac{1}{2} \left( \frac{r}{r_0} \right)^2 \right],$$

where $l$ is the orbital angular momentum in the two-nucleon system, $N$ is a normalization factor, and $r_0$ is a scale parameter.
After exclusion of inner channel one gets the effective Hamiltonian in external NN channel:

\[
H_{\text{eff}}(E) = h_{NN} + \frac{\lambda_1^2 |\phi\rangle\langle\phi|}{E - E_D}.
\]  

(3)

Due to the separable form of the basic term in the effective Hamiltonian (3) one can determine explicitly the additional \(t\)-matrix in the distorted-wave representation:

\[
t(E) = \frac{\lambda_1^2 |\phi\rangle\langle\phi|}{E + i0 - E_D - J_1(E)},
\]  

(4)

where \(J_1(z)\) is the matrix element of the resolvent of the external \(NN\) Hamiltonian \(g_{NN}(Z) = [z - h_{NN}]^{-1}\):

\[
J_1(Z) = \lambda_1^2 \langle \phi | g_{NN}(z) | \phi \rangle.
\]  

(5)

\[
\text{Im}J_1(E + i0) = -\pi |\langle \phi | \psi(E) \rangle|^2,
\]
Note that the imaginary part of this function at a real positive energy can be found in an explicit form as

$$\text{Im} J_1(E + i0) = -\pi |\langle \phi | \psi(E) \rangle|^2,$$

(6)

where $\psi_0(E)$ is the scattering function for the external Hamiltonian $h_{NN}$.

From (4) one can easily obtain the expression for the total $S$-matrix:

$$S(E) = e^{2i\delta_0} \frac{E - E_D - J_1^*(E + i0)}{E - E_D - J_1(E + i0)},$$

(7)

where $\delta_0(E)$ is the phase shift for the external Hamiltonian $h_{NN}$. Thus, the pole of the total $S$-matrix can be found in a complex energy $z$ plane from the condition:

$$z - E_D - J_1(z) = 0.$$

(8)
The condition (8) makes it possible to find the position of the “dressed” dibaryon resonance whereas the complex value of $E_D$ determines a “bare” complex pole. The complex function $J_1(z)$ gives shifts for the real and imaginary parts of the initial dibaryon pole and thus determines the parameters (mass and width) for the dressed dibaryon. The dressing procedure can be represented graphically by the diagram series similar to that in the field theory (Dyson equation):

$$
\begin{align*}
\text{N} & \quad \text{N} \\
\text{D} & \quad \text{D} \\
\text{N} & \quad \text{N} \\
\end{align*}
\quad = 
\begin{align*}
\text{N} & \quad \text{N} \\
\text{D}_0 & \quad \text{N} \\
\text{N} & \quad \text{N} \\
\end{align*}
\quad + 
\begin{align*}
\text{N} & \quad \text{N} \\
\text{D}_0 & \quad \text{D}_0 \\
\text{N} & \quad \text{N} \\
\end{align*}
\quad + \ldots
$$

Fig. 1: The sum of terms corresponding to dressing of the total dibaryon propagator. $D_0$ and $D$ are the propagators of the “bare” and “dressed” dibaryons, respectively.
In our two-channel model we have a simple separable coupling between inner and external (OPEP) channels. Thus in the model the $NN$ scattering is dominated by OPEP and a single dibaryon pole in a particular $lst$ channel.
Let’s consider at the beginning some isovector channels $^3P_2$, $^1D_2$ and $^3F_3$. We have chosen these partial channels because the numerous preliminary studies have found the dibaryon resonances in these channels rather reliably.

To describe the $NN$ phase shifts in given channel (lstat) we choose the parameters in the effective Hamiltonian (3): $\lambda_1$, $E_D = E_0 - i\Gamma_D/2$ and $r_0$ in form factor $\phi$ from the best fit to the real part of phase shifts in large energy interval 0 - 600 MeV (or even 0 – 800 MeV).

To describe the inelastic processes (the decay of the dibaryon resonance into different hadronic channels like $NN\pi$, $N\Delta$, $\Delta\Delta$ etc.) we use the energy-dependent width with a smoothed step-like dependence:

$$\Gamma_D(E) = \Gamma_0 \left[1 + \exp \left(\frac{E_{thr} - E}{\alpha}\right)\right]^{-1} \quad (9)$$

where $\alpha$ is a smoothing parameter ($\approx 0.02$ GeV).

We have obtained the following results:
Fig. 2: Real (a) and imaginary (b) parts of the partial $NN$ phase shifts in the $^3P_2$ channel (solid curves) in comparison with the SAID data (points).
We see that the single-pole model in a combination with a simple OPEP provides quantitative description not only real part of $^3P_2$ phase shift as high as 700 MeV but also its imaginary part until 700 MeV.

And the most interesting our result: we found the following parameters for the dressed dibaryon:

$$M_{\text{th}}(^3P_2) = 2.22 \text{ GeV} \quad \text{and} \quad \Gamma_{\text{th}}(^3P_2) = 0.095 \text{ GeV},$$

while their experimental values found by the ANKE-COSY Collaboration are

$$M_{\text{exp}}(^3P_2) = 2.197(8) \text{ GeV} \quad \text{and} \quad \Gamma_{\text{exp}}(^3P_2) = 0.130(21) \text{ GeV},$$

where the numbers in parentheses denote the error in the last digit.

Thus, the mass and width for the $^3P_2$ dibaryon obtained within the single-pole model turn out to be very close to their experimental values.
Now let’s compare these results with the conventional picture.

In the conventional realistic NN potentials we have many potential terms (central, $\vec{S}\vec{L}$, $(\vec{S}\vec{L})^2$, $L^2$ etc.) each of them being a lot of radial functions corresponding to $\pi$-, $\rho$-, $\omega$-, $\sigma$-meson exchanges. And this whole complex structure is able to describe NN real phase shifts only up to 350 MeV.

Contrary to this, the dibaryon concept can reproduce both real and imaginary parts of phase shifts until 600 – 800 MeV, with basic parameters which are in a very good agreement with those experimentally found for dibaryon resonances!
Channel $^1D_2$

A fully similar consideration for $NN$ phase shifts in the singlet channel $^1D_2$ leads to theoretical predictions shown in Fig. 3.

Fig. 3: Real (a) and imaginary (b) parts of the partial $NN$ phase shifts in the $1D2$ channel (solid curves) in comparison with the SAID data (points).
The parameters of the dressed dibaryon in the $^1D_2$ channel found within our model are following:

\[ M_{\text{th}}(^1D_2) = 2.175 \text{ GeV}, \quad \Gamma_{\text{th}}(^1D_2) = 0.104 \text{ GeV}, \]

while their experimental values are:

\[ M_{\text{exp}}(^1D_2) = 2.160 \text{ GeV}, \quad \Gamma_{\text{exp}}(^1D_2) = 0.120 \text{ GeV}. \]

Thus, we see again very reasonable agreement between theoretical predictions and experimental findings.
Channel $^{3}F_{3}$

First experimental evidence of the $^{3}F_{3}$ dibaryon resonance with the mass $M_{D} \approx 2.26$ GeV was obtained in 1977. It was also established that there is a very large inelasticity in the $^{3}F_{3}$ $NN$ partial wave. So, an interesting and challenging question arises: to what degree the $^{3}F_{3}$ resonance contributes to the real and imaginary parts of the $NN$ phase shifts in this channel.

From the first glance, the possible impact of the dibaryon can be seen mainly at the energies close to the resonance position. However, this is not the case: the influence of the $s$-channel dibaryon exchange is also traced far from the resonance energy. Comparison between theoretical predictions and empirical data (SAID) for real and imaginary parts of $^{3}F_{3}$ phase shifts is shown in Fig. 4.
Fig. 4: Real (a) and imaginary (b) parts of the partial $NN$ phase shifts in the $^3F_3$ channel for different values of the OPEP cutoff parameter: $\Lambda = 0.85$ GeV (dash-dotted curves) and 0.65 GeV (solid curves) in comparison with the SAID data (points).
As is clearly seen from the figure, the single $^3F_3$ pole (in a combination with OPEP) can reproduce almost quantitatively the real $NN$ phase shift from zero energy up to 700 MeV. The imaginary part of the phase shifts turns out to be underestimated in this case. This is due to the presence of very large inelasticity in the $^3F_3$ channel which is explained by a large coupling $NN$ and $N\Delta$ channels:

$$NN \Leftrightarrow N\Delta \Leftrightarrow NN$$

So, to describe the imaginary part of phase shifts in this channel one needs to include additionally $N\Delta$ channel:

$$NN \,(^3F_3) \Leftrightarrow N\Delta \,(^5P_3).$$

When comparing the theoretical and experimental dibaryon parameters we find again very reasonable agreement:

$$M_{th}(^3F_3)=2.226 \text{ GeV}, \quad \Gamma_{th}(^3F_3)=0.156 \text{ GeV}$$

and

$$M_{exp}(^3F_3)=2.260 \text{ GeV}, \quad \Gamma_{exp}(^3F_3)=0.200 \text{ GeV}.$$
By using the developed model, we can also readily estimate the $NN$ part of the total dibaryon width by simply comparing the values of $\Gamma_0$ and $\Gamma_{th}$. Thus, the decay width into the $NN$ channel turns out to be about 22%, 29% and 23% of the total width for the $^3P_2$, $^1D_2$ and $^3F_3$ resonances, respectively. These values agree qualitatively with the previous estimates which typically give the $D \rightarrow NN$ partial width to be 10 - 20% of the total width for the isovector dibaryons.
**Channel $^1S_0$. Description of repulsive core effects.**

The NN repulsive core is one of the main ingredients of conventional models for $NN$ interaction. According to the basic meson-exchange paradigm it is originated from vector-meson exchanges. However, from the modern point of view this concept looks doubtful. E.g. authors of the paper (T. Barnes, S. Capstick, M.D. Kovarik, E.S. Swanson, Phys.Rev. C 48, 539 (1993)) claim:

“A literal attribution of the short-range repulsive core to vector meson exchange, as opposed to a phenomenological parameterization, of course involves a non sequitur: since the nucleons have radii $\approx 0.8$ fm and the range of the vector exchange force is $\hbar/m_\omega c \approx 0.2$ fm one would have to superimpose the nucleon wavefunctions to reach the appropriate internucleon separations. The picture of distinct nucleons exchanging a physical $\omega$-meson at such a small separation is clearly a fiction..."
The dibaryon model (see V.I. Kukulin et al., J. Phys. G 27, 1851 (2001); Ann. Phys. 325, 173 (2010)) predicts for the S-wave $NN$ interaction the dominating six-quark configuration of the type $|s^4p^2[42]_xLST\rangle$ with a two harmonic oscillator quanta ($2\hbar\omega$) excitation. When projecting this $2\hbar\omega$-excited configuration onto the $NN$ channel, the $NN$ relative motion wavefunction $\psi(r)$ automatically acquires an internal node (see Fig. 5). The node position ($r_c \approx 0.5$ fm) turns out to be very close to that of the traditional repulsive core. It is very interesting that this node is very stable at variation of collision energy.
Fig. 5: Behavior of radial wave functions of $NN$ scattering in the $^{1}S_0$ channel at different collision energies.
In the dibaryon model appearance of a stationary node in the $S$-wave $NN$ interaction is provided by an orthogonality condition between the fully symmetric and the mixed-symmetry six-quark configurations, which is realized by including an additional projecting operator in the $NN$ potential:

$$V_{rep} = \lambda |\phi_0\rangle \langle \phi_0|,$$

where $\lambda \rightarrow \infty$ and $\phi_0$ is a projection of the fully symmetric wavefunction $|s^6[6]\rangle$ onto the $NN$ channel. Fortunately, this modification does not add to our model any free parameters, so that the number of adjustable parameters for the bare dibaryon remains minimal.

In Fig. 6 we show the results for two possible positions of the bare resonance pole ($M_D = 2.245$ and 2.427 GeV). Both of them allow to reproduce the real and imaginary parts of the $^1S_0$ phase shifts up to the energies $E_{\text{lab}}$ corresponding to $M_D$ values.
Fig. 6: Real (a) and imaginary (b) parts of the partial $NN$ phase shifts in the $1S0$ channel found with the bare dibaryon masses $MD = 2.245$ GeV (dash-dotted curves) and $2.427$ GeV (solid curves) in comparison with the SAID data (points).
We found the following parameters for dressed dibaryon in \(^1S_0\) channel for two variants of model with \(M_D = 2.245\) and 2.427 GeV, accordingly:

\[
M_{\text{th}}(^{1S_0})=2.42 \text{ GeV}, \quad \Gamma_{\text{th}}(^{1S_0})=0.44 \text{ GeV},
\]

and

\[
M_{\text{th}}(^{1S_0})=2.77 \text{ GeV}, \quad \Gamma_{\text{th}}(^{1S_0})=0.80 \text{ GeV}.
\]

These results can imply existence of a second high-lying dibaryon in the \(^1S_0\) channel. The first near-threshold dibaryon pole in the \(^1S_0\) channel corresponds to well known singlet deuteron predicted by Dyson and Xuong many years ago.
Summary

The most important our finding is the fact that many NN amplitudes for elastic and inelastic scattering up to rather high energies 600 – 800 MeV can be quantitatively described by a single dibaryon production with basic parameters being coincide or are rather close to those experimentally observed by different experimental groups.

This conclusion contradicts to the dominating current belief about the meson-exchange nature of nuclear force.
Thank You
For Your Attention!