Properties of bound states in QCD(QED) and nuclear theory

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The strictly derived properties of QCD together with the Standard Model of Electroweak Interactions and Gravity allow to identify and resolve some fundamental puzzles in the non-relativistic theory of a nucleon, of nucleus, of their interactions, to find the phenomena specific for the cold superdense nuclear matter(of an inner core of a heavy neutron star).

The application of the non-relativistic theory of a bound state in QCD(QED) to the description of the amplitudes of high energy processes off a bound state violates the exact predictions of QCD(QED) such as the sum rules for the valence quarks, momentum sum rules, contradicts to the Wilson operator expansion, leads to the violation of electric, baryon charges, of equality of inert and gravitational masses of a bound state, leads to the large fake corrections to the amplitudes of high energy processes.
The origin of the puzzle is the fundamental difference in the normalization of the wave function of a bound state in a quantum field theory and in the quantum mechanics. In a quantum field theory the normalization of wf of a bound state follows from the matrix element of a conserved current at zero momentum transfer. (S.Mandelstam 1952) The calculation of a conserved charge of a bound state includes the relativistic form of a conserved current and vacuum fluctuations. In QED the same mismatch leads to the tiny but important correction to the modern theory of hydrogen atom. In the nuclear physics the mismatch is significantly larger due to significant probability of SRC. The formal reason of the puzzle is the different realization of local symmetries in the non-relativistic and relativistic physics. With the increase of nucleon densities(inner core of a heavy neutron star) the role of relativistic effects is increasing.

The value of the fake correction to the structure functions of ed scattering calculated in the impulse approximation by G.West using non-relativistic theory of the deuteron is comparable with the nuclear shadowing effects. If to account for the baryon charge according to the rules dictated by a quantum field theory West correction disappears from the theory and even from the presentation of the SLAC data .(Frankfurt-Strikman 1977)

The precision of the conservation of electric and baryon charges, validity of Newton law have been established with significantly better accuracy than the violation of these laws in the non-relativistic nuclear theory. This puzzle and its resolution demonstrates necessity of the accurate account of relativistic effects in the nuclear physics and in the theory of hydrogen atom in QED. Light-cone quantum mechanical theory of a nucleus has no such a problem and well reproduce basic results of nuclear theory.

Structure of a nucleon in QCD

1. The vacuum of the non-perturbative QCD.

V.Gribov suggested that running coupling constant is frozen at small value at the virtualities around few GeV^2. Experimental confirmations are:

i. the data electron-positron annihilation into hadrons. cf. Dokshitzer, Gavin Salam.

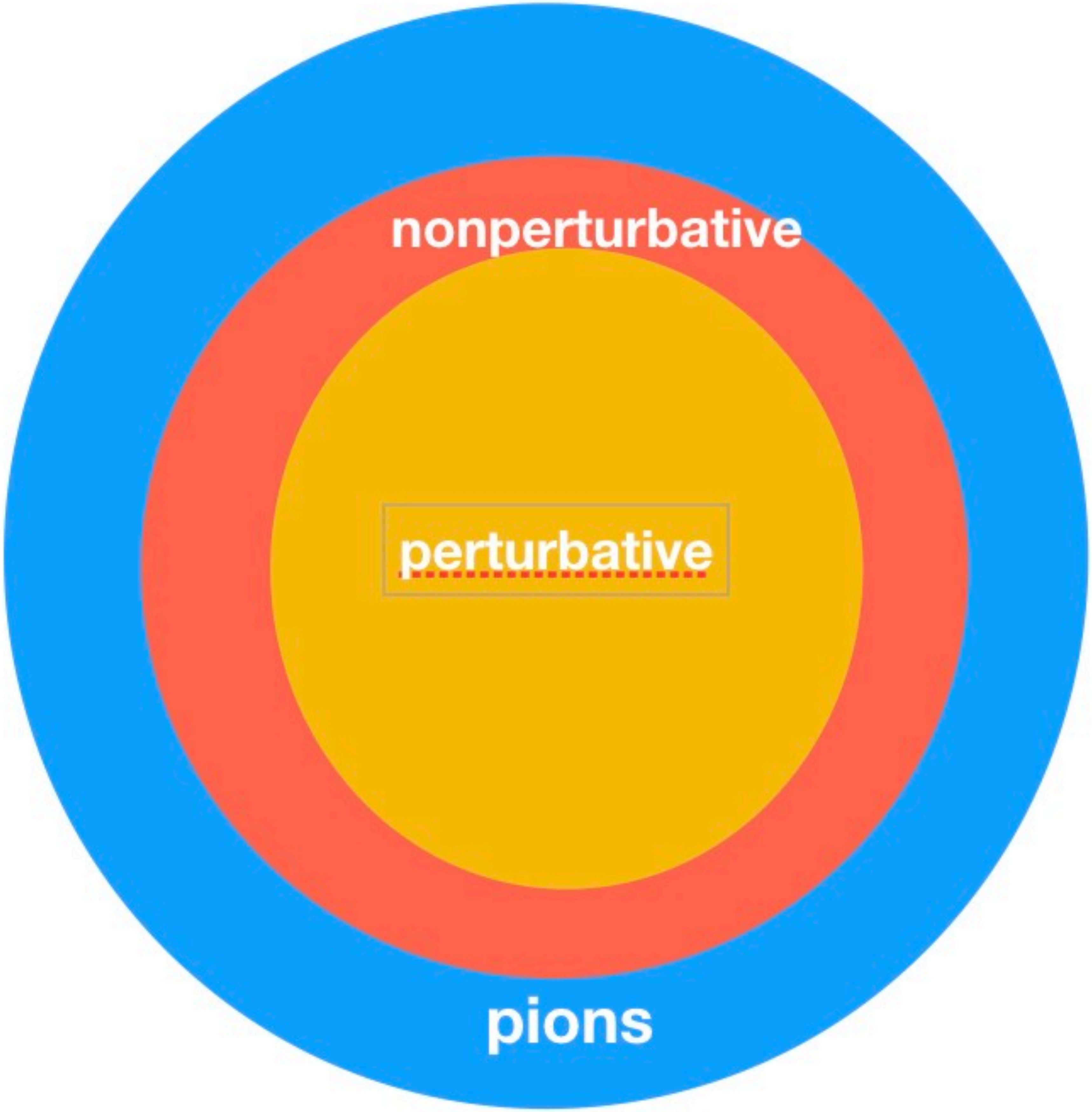
ii. Vainstein, Schifman, Zakharov(VSZ) calculated within the method of dispersion sum rules the main properties of the ground state of mesons rho, pi.... They accounted for the quark and gluon condensate pairs only.

iii. B.Ioffe calculated within this method the mass of a nucleon in terms of the condensate of quark pairs.

iv. It seems now that QCD vacuum is dominated by quark and gluon condensates cf. also Gell-Mann-Leutwiller description of the phenomenon of spontaneously broken chiral symmetry.

Thus QCD resembles QED theory of superconductivity in the Gorkov formulation.

2. The coordinate space analysis of the vacuum correlator of the currents with the quantum numbers of a nucleon +knowledge of the vacuum of QCD allow to reconstruct the wave function of a nucleon within the method of dispersion rules.


nonperturbative
perturbative
pions

The low energy nuclear physics: the attraction is dominated by the interaction of pion clouds of interacting nucleons whose thickness is around 0.2 Fm. This thickness is calculated directly (Braun-Balitsky) and/or by subtracting the region occupied by color from the average quadratic radius of a nucleon. The answer is practically the same. Dominant dynamics of NN interaction for the average inter-nucleon distances in a nucleus is spontaneously broken chiral symmetry, Chiral QCD Lagrangian, EFT. Localization of pion cloud on the surface of a nucleon differs from that within the preQCD approaches where point-like pion-nucleon interaction was starting point. Meson exchanges with large virtualities are strongly suppressed or zero. Pion-nucleon form factor oscillates. The predictions on the pion condensation within a star is in variance with QCD.

The short-range inter-nucleon repulsion is due to the inter-nucleon interaction of non-perturbative layers where quarks and gluons interact with the vacuum condensates. Low energy nuclear physics gives no clue on the properties of repulsion except its large value.(Feshbach-Kerman) The measurement of high momentum tail in high energy processes allows to restrict the form and the properties of repulsive potential which plays crucial role in the evaluation of maximal mass of a heavy neutron star.

The radius of pQCD region within a nucleon is around 0.5Fm. The derivation uses the analysis of Shyryak of the correlator of currents in the coordinate space. Pion clouds are impossible if inter-nucleon distances would be much smaller than 1Fm where pQCD regions overlap. Thus at extremely large densities chiral symmetry is restored and pion clouds disappear. The restoration of chiral symmetry at extremely large densities predicted by QCD is the phenomenon opposite to the hypothesis on pion condensates in the interiour of a heavy neutron star.

- DIS, hard diffractive processes probe center of a nucleon i.e.PQCD plus non-perturbative QCD layers. So the relationship between low energy processes and hard nuclear phenomena is indirect but exists and reveals itself in the phenomena investigated in a lab.

The non-perturbative layer accounts for the interaction of quarks and gluons with the condensate pairs. Quarks obtain significant mass within this layer -as the result of pQCD evolution and the interaction with the condensate pairs. Quarks in the non-perturbative layer resemble constituent quarks. Thus the presence of non-perturbative layer distinguishes QCD from the bag models.

- The radius of the region occupied by color within a nucleon in DIS unambigously follows from the exact valence quark sum rule:

$$\int dx[V_{A,m}(x, Q^2, t)] = F_m F_V (t)$$

In the above formulae t is the momentum transfer, Fm is the operator of SU(3) and Fv is the component of electromagnetic form factor of a nucleon . This model independent sum rule has been derived before the onset of QCD as the theory of strong interactions. (Fubini....) A modern derivation uses Wilson operator expansion. E.m. form factor of a nucleon is known-so the radius of the sum of pQCD and non-perturbative QCD regions within a nucleon is around 0.65 Fm. Similar radius follows from the gluon form form factor of a nucleon measured in the hard diffractive processes.

Significant role of color in the wf of a hadron has been observed

1.In the hard diffractive photoproduction of J/\psi in the dependence on energy, in the universality of gluon form factor of a nucleon.

2. In the CT phenomena observed at FNAL in the diffractive production of 2 jets off a nuclear target, in the diffractive electroproduction of rho meson off a nuclear target.

3. In the hard multi-parton collisions at LHC

The onset of the restoration of chiral symmetry in the nuclear phenomena-related with the dynamics relevant for the stability of neutron stars.

- 1. The attractive potential of NN interaction is due to 2 pion exchange -common wisdom in the nuclear theory..
- 2. The contribution of pion cloud of a nucleon with momenta around pion mass does not influence the nucleon structure-this contribution is described by Chiral QCD Lagrangian.
- 3. To describe S, D phases the contribution of Delta isobar in the intermediate state of attractive potential is often accounted for(Wiringa, Epfelbaum) This part of the potential influences the inner structure of an interacting nucleon. It can not be described within the Chiral Lagrangian of Weinberg. This part corresponds to the large momentum component of nucleus wave function i.e. SRC.

The exchange between nucleons by two pions with large momenta i.e. the interference of pion fields of interacting nucleon reproduces the pion field

of one nucleon. This is equivalent to the suppression of the total pion cloud of two nucleons. Thus pion cloud pressure to the kernel of a nucleon is decreasing and quarks propagates within the larger spatial region. This is one of the phenomena leading to the EMC effect. The DY data shown by Mark found nuclear suppression of antiquark distribution in a nucleus for x larger than 0.4 i.e. suppression of pion field in a nucleus.

- Together recent DY data and smallness of antiquark distribution in a nucleon, nucleus at x larger than 0.2 practically kills the hypothesis that short-range inter-nucleon interaction is due to the exchange by highly virtual mesons rho,omega...

Suppose nucleon density is increasing. So inter-nucleon distances becomes smaller than one Fermi. At these distances repulsion become to dominate. In this case:
i.pion field will continue to decrease with the increase of density but
ii. quark momentum distribution will tend to increase large momentum tail- inverse the EMC effect. Difficult to observe this effect since experiments investigate phenomena in the momentum space but relationship between momentum space and coordinate space description is complicated. Tensor forces tends to hide the effects of small inter-nucleon distances.

Conclusions

The observation of SRC and investigation of its quark-gluon structure is the road to the QCD dynamics of inner core of neutron stars.