Sea quarks revisited

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Abstract

In this letter we derive a relation which shows that sea quarks while briefly orbiting inside a nucleon are not only generated in the gluon field of the strong interaction or through vacuum fluctuations, but rather created by the constantly released electromagnetic energy between the charged, short-lived $u\bar{u}$ and $d\bar{d}$ sea quark and antiquark pairs, a model, which can also explain the unexpected large mass of a nucleon and the two directions of the nucleon's spin.

1. Introduction

According to the current opinion, in the field of strong interaction, which is mediated by gluons, virtual quark-antiquark pairs appear, which are created as vacuum or gluon fluctuations and are immediately destroyed again. This process creates a "sea" of gluons, quarks and antiquarks around the actual valence quark (1). Sea quarks in the proton are virtual up and down quarks and antiquarks and, to a lesser extent, strange (anti)quarks. In 2022, a small fraction of charm (anti)quarks was detected (2). The contribution of these sea quarks to the mass of a nucleon as well as their kinetics inside a nucleon is still the subject of debates. While the influence of the strong interaction on the generation of sea-quarks has been studied in depth, little is known about the creation and kinetics of sea quarks governed by the gravitational and electromagnetic (EM) force inside a nucleon.

In this letter we present a model (α-model), which establishes the leading role of the released electromagnetic energy following virtual pair annihilation on the steady creation of new sea quark pairs and which deepens the understanding of the orbital kinetics of sea quarks inside a nucleon, offering a useful contribution to the decades-long spin-crisis and protons' mass calculations.

2. Gravity and kinetics of the sea quarks

All nucleons have an intrinsic angular momentum of $\hbar/2$, even if this does not correspond to a macroscopic rotation of the nucleons. However, there are indications that the virtual sea quarks in a nucleon commonly rotate due to the gravitational attraction by the other sea quarks with probably changing axes of rotation and a periodicity of 4π, comparable to DeBroglie matter waves (3,4).

The gravitational force caused by the mass of the sea quarks is always perpendicular to the direction of movement of the quarks, which, simplified illustrated, orbit about 4-8 times within their short lifetime forming a circle or ellipse before the pairs disappear, while their main axis moves forward with the frequency f (Fig. 1, red arrow). Hence, the totality of the resulting gravitational forces causes the sea of quarks to rotate, probably with alternating axes over 4π.

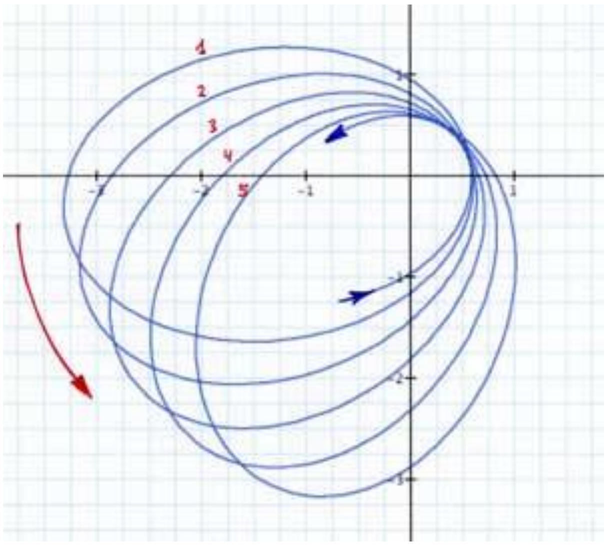

Fig. 1:
Orbit of a sea quark inside the nucleon (blue lines), while the main axis of the ellipse moves forward with the velocity $2\pi r f$ (red arrow), inducing a common rotation of the sea. In this figure 5 circuits are tranced (red numbers). The blue arrows show the beginning and end of the distance travelled by the sea quark during its lifetime as well as the direction (here counterclockwise) inside the nucleon.

The frequency f of rotation is calculated as $g_p eB/4\pi m = 2.179\ kHz$.

$$E = hf = m\, x\, B = g_p \frac{e}{2m}\frac{h}{2\pi}B; \quad f = \frac{g_p eB}{4\pi m} = 2.179\ kHz \qquad [1]$$

(B ist the magnetic flux density = 51.2 μT derived from the magnetic moment of a proton). The quarks in the quark sea, which consists of negatively and positively charged quarks and antiquarks, have a certain, defined distance from each other due to the Coulomb attraction and repulsion. Due to their rapid joint rotation, they form a density gradient of m/r^2. In one whole rotation of the sea, about 10^{18} pairs are formed successively, while in average 137.035/2,467 = 55.55 sea quark pairs [4] and 3 valence quarks are present at once. It is also known that more (anti)-d quarks than (anti)-u quarks are formed in the quark sea (6). If we assume that the anti-d quarks with positive charge outweigh the anti-u quarks with negative charge and that the distribution of the anti-d quarks is asymmetrical in relation to the periodicity of rotation of the quarks but evenly distributed on average over time, an inward-directed, asymmetrical rotation similar to a sine wave is created, but this is repeated at intervals of 4π, since the axis of rotation tilts for example downwards during one rotation period and back again during the next. The spherical, symmetrical uniform distribution within two rotation periods (4π) probably results from the distribution of the quarks' frequency in the light of the Heisenberg uncertainty expressed as $\Delta E \Delta t \geq h/4\pi$ (φ is the periodicity of equal distribution).

$$\Delta t = \frac{h}{4\pi\Delta E} = \frac{1}{f\varphi} = \frac{h}{\Delta E\varphi}; \quad \varphi = 4\pi \qquad [2]$$

3. The Coulomb force between sea quarks

For sea quarks the following applies: $2(E_d + E_u)$ plus the sea quarks' (and gluons') kinetic energy is equal to the EM energy (E_C) between the u, d sea quark/antiquark pairs in a nucleon, considering the assumption [1] (α is the fine structure constant).

$$E_{C,u,\bar{u},d,\bar{d}} = \frac{-\frac{10}{9}e2k}{\frac{r}{2}}; \quad \frac{-\frac{20}{9}\hbar c\alpha}{r} = \frac{-\frac{20}{9}mc^2\alpha r}{4r} = E_c; \quad \frac{-\frac{5}{9}mc^2\alpha r}{r} = E_c$$

$$mc^2 = \frac{9Ec}{5\alpha}; \quad mc^2 - E_{v,s,g} = 9\left(1 - \frac{E_{v,s,g}}{mc^2}\right)E_C/5\alpha =$$

$$= n\big(E_d + E_u + (E_s)\big) + mE_{kin,s,g} \qquad [3]$$

This might ultimately answer the question about the unexpected large mass of a nucleon, which ist still a subject of debates. Based on the equation [3] the cause of the formation of the sea quarks can thus be traced back to the resolution of the Coulomb energy between the very short-lived (+/- charged) sea quark pairs themselves, which suddenly disappear and thereby constantly produce new quark pairs (the Coulomb energy is released), instead of the strong nuclear force as the sole cause, as previously assumed. Most of the virtual quark-antiquark pairs therefore do not appear as vacuum fluctuations or in the gluon field of the strong interaction. The dissolution of the quark pair creates electromagnetic radiation, the strong interaction between them generates virtual quark/antiquark pairs (and gluons) probably in a minor amount.

Uncertainties in the derivation of this relation arise from the masses of the u and d quarks, which are not precisely known (here we took 4.6 and 2.15 MeV) and from the Coulomb energy, for the calculation of which the exact constellation of the electrical charges and individual distances would have to be known in detail. In a simplified representation, however, a u quark interacts with its u antiquark counterpart in a distance $4r/\pi$ from each other (Fig. 2) and also with the rest of the charges ($q = +1$) in a proton (but not in a neutron), in a distance r (distance to the charge +1, which appears to be concentrated in the center). Summing the square charges for the sea quarks calculated in this way, the relation (1-1/3)·1/3+(1-2/3)·2/3+(1+1/3)·(-1/3)+(1+2/3)·(-2/3)=-10/9e^2 for an $u, \bar{u}, d$ and $\bar{d}$ quark would result (also -10/9 for a neutron).

The mechanism behind virtual quark/antiquark pair formation by the released EM energy proposed in this letter is that within the field of a nucleon the majority of the energy of a (virtual) gamma-photon, which is generated by the release of EM energy, is converted into the mass of the two quarks and their kinetic energy. The photon's energy is thereby at least equal to the sum of the rest energies of the quark and antiquark (equation [3]). Another example that demonstrates that quark pairs can be generated by the energy of a (virtual) photon as an intermediate step is the formation of quark-antiquark pairs during the collision of electrons and positrons $e^- + e^+ \rightarrow \; q + \bar{q}$, in which a virtual photon or Z_0 boson is created first. Here, two hadron jets are observed in opposing directions. A three-jet event occurs when a high-energy gluon is also emitted, which also carries a color charge and is therefore also hadronized.

4. Discussion

4.1. Sea quarks' contribution to the nucleon's mass

Special relativity accounts for the bulk of the mass of protons and neutrons in the modern theory of the nuclear force. The mass of a proton is between 80 and 100 times greater than the sum of the rest masses of its three valence quarks, whereas the gluons have no rest mass. According to current knowledge, as compared to the rest energy of the quarks alone in the QCD vacuum, the extra energy of the quarks and gluons in a proton account for almost 99% of the proton's mass. The rest mass of a proton is, thus, the invariant mass of the system of moving quarks and gluons that make up the particle. In such systems, even the energy of massless particles confined to a system is still measured as part of the rest mass of the system (8).

Using lattice QCD calculations, the contributions to the mass of the proton are the quark condensate (~9%), comprising the up and down quarks and a sea of virtual quarks, the quark kinetic energy (~32%), the gluon kinetic energy (~37%), and the anomalous gluonic contribution (~23%), comprising contributions from condensates of all quark flavors (9).

The internal dynamics of protons are complicated by the quarks exchanging gluons and interacting with various vacuum condensates. The mass of a proton can be calculated directly from the theory to any accuracy with Lattice QCD. The mass is determined to better than 4% accuracy according to the most recent calculations (10). Quarks as light as they are in the real world make these assertions still controversial. This means that the predictions are found through a process of extrapolation, which can introduce systematic errors (11). It is difficult to determine whether these errors are controlled properly, since the quantities that are compared to experiment are the masses of the hadrons, which are known in advance.

These recent calculations are carried out by supercomputers, and, as noted by Boffi and Pasquini, a comprehensive description of the nucleon structure is still lacking due to the requirement for nonperturbative and/or numerical treatment of long-distance behavior (12). The topological soliton approach, originating from Tony Skyrme, and the more precise AdS/QCD approach, which extends it to encompass a string theory of gluons (13) as well as various QCD-inspired models such as the bag model and the constituent quark model, which gained popularity in the 1980s, and the SVZ sum rules, which facilitate rough approximate mass calculations (14). These methods, however, do not possess the same level of precision as the lattice QCD methods.

Attributing the rest mass $m_n - m_{valence}$ of a nucleon to a constant mass of the quark sea, which is constituted by quark/antiquark pairs, is not a new idea, but the derivation of the actual amount of the mass of the quark-sea by about 137.035/2.467 = $0.4/\alpha$ simultaneously present quark/antiquark pairs has, to our knowledge, not been published before. Therefore, it might offer a model, which could enter into mass calculations, while in this model the sea-quarks' contribution far exceeds the portion calculated in the lattice QCD (9) and the quark (and gluon) kinetic energy contributes to about 60% to the total rest mass of nucleons, which fits the data from the lattice QCD. Given the complexity and transience of the processes in the nucleon and quark sea, the relation [4] based on released EM field energy is able to explain, why the mass of a nucleon shows the observed constancy of an atomic clock, while the strong field energy cannot.

4.2. Sea quarks' contribution to the nucleon's spin

In order to solve the "spin crisis", experiments were developed that measure the spin distribution of quarks and gluons in the proton and neutron. The focus of the HERMES experiment at DESY was to determine the spin orientation of the quarks separately according to their flavor (up, down, strange). These measurements (supplemented by the CERN experiment team) show that the polarization of the strange quarks and the other sea quarks is negligibly small and therefore does not explain the spin puzzle. This leaves only one explanation for the spin puzzle: the orbital angular momentum of quarks and/or gluons contributes significantly to the spin of the proton. Recently, it has been possible to carry out measurements of the orbital angular momentum of the quarks. According to a recently published work by Anthony Thomas, these are consistent with the lattice gauge theory and the modern model of the nucleon (15). Measuring the orbital angular momentum of quarks and gluons is anything but trivial. Theoretical developments have led to new definitions of the orbital angular momentum in relativistic field theory and to the introduction of generalized parton distributions (GPD), a generalization of the known parton distributions (PDF). In contrast to PDFs, which describe the longitudinal momentum distribution of the quarks and gluons in the nucleon, GPDs also contain information about the transverse spatial distribution of the quarks. In analogy to the classical calculation of the angular momentum from position and momentum, X. Ji was able to show that the total contribution of the angular momentum for each quark can be calculated directly from the GPD functions. These GPD functions are not very intuitive at first. In a certain sense, they generalize the Wigner function from classical quantum mechanics to quantum field theory. In 1932, Wigner defined a real function in the quantum mechanical phase space that completely describes quantum mechanical systems (16). Experimental access to GPDs is provided by exclusive hard scattering processes, especially the scattering of high-energy leptons on nucleons with exactly three particles in the final state: a proton, lepton and photon. Since GPDs are multi-dimensional functions, it has not yet been possible to make clear statements about the orbital angular momentum using experiments. Nevertheless, under certain model assumptions, initial experimental values for the angular momentum can be extracted. Accordingly, the total angular momentum contribution of the up quarks is large and positive at around 40%, while the contribution of the down quarks is small. Anthony Thomas interprets the result using various models: In a non-relativistic quark model, the spins of the valence quarks generate the entire proton spin. In a relativistic quark model (e.g., Bag model), the Heisenberg uncertainty principle adds a movement of the quarks, which reduces the spin component to 65%. Thomas shows in his analysis that the exchange of gluons in the lowest order (one-gluon exchange hyperfine interaction), as used in many areas of QCD, reduces the component to 50%. Due to the chiral symmetry breaking of QCD, many non-perturbative effects of QCD can be described by effective field theories in which the degrees of freedom are no longer assigned to quarks and gluons, but to pions and other mesons. Then virtual "pion clouds" also contribute to the angular momentum. At the model's energy scale of $0.4\ GeV^2$, up quarks essentially form the spin of the proton, and the orbital angular momentum of the quarks makes up a total of 62% of the proton's spin. After transforming the results to a scale of about $2\ GeV^2$, the results can be compared with the measurements (17) and the calculations of the lattice gauge theory.

The fact that the sea seams to move around with the frequency 2.179 kHz in protons can be explained by a consistent gravity inside a nucleon ($mv^2/r = m^2G/r^2$). The spike in the polarizability curve of protons $at\ Q2\ =\ 0.33\ GeV^2$, recently published in the journal Nature (18), provides reliable evidence that it could be an interference in the sense of a superposition of the particle wave of the scattered electrons with the rotational wave of the protons at the same energy, which doubles the expected curve value, and, in the absence of any other explanation, proves the calculated rotational wave frequency of the quark sea. There are, moreover, indications, that not the velocity of rotation, but rather the radius of a nucleon ($R = c/8\pi f$) is quantized und virtually oversized (19). Moreover, the 1/2 spin of the nucleons was shown to be given by the Heisenberg uncertainty principle $\Delta L\Delta\varphi = \Delta L \cdot 2\pi >= h/2;\ \Delta L >= h/4\pi$ (P.A. Millette 2015 (5), $\Delta\varphi$ is the maximum angle). ΔL is measured as $h/4\pi$, since, according to Heisenberg, no smaller value can be measured (9). This would consistently explain why an elemental particle like an electron has the same spin as the more complex, composed nucleon. In this light it would make no sense to search for the participation of the quarks on the proton's spin, which is a quantized (oversized) quantity, and therefore, below a value of $h/4\pi$ it cannot be treated like an angular momentum with its sum rules.

4.3. Sea quark creation and interactions inside a nucleon

It is known that the spatial separation of quarks, i.e., an increase in the distance, leads to very strong gluon fields between them. The field energy is sufficient to form at least one pair of quark and corresponding antiquark via the mechanism of pair formation. These quark pairs in turn form color-neutral (also called 'white') mesons. The color neutrality means that strong interaction no longer occurs. The strong interaction is purely formal and Yukawa-consistently infinite, but an absence of color-charged particles at certain points in the Fermi range leads to their disappearance. The contribution of the sea quarks is very difficult to calculate because the largest contributions come from an energy range in which the coupling constant of the strong interaction is very large and therefore the perturbation series no longer converges. In addition, the calculations of the contribution of sea quarks concentrate on the strong interaction as the cause of sea quark generation and the mathematical models that exist may not reflect the real constellation and/or underestimate the amount of sea quarks and could therefore not be valid. Hence, it would be desirable taking the intuitively more consistent and calculable cause of the released electromagnetic energy between quark/antiquark pairs into consideration, when talking in future about the origin of the quark sea surrounding the valence quarks.

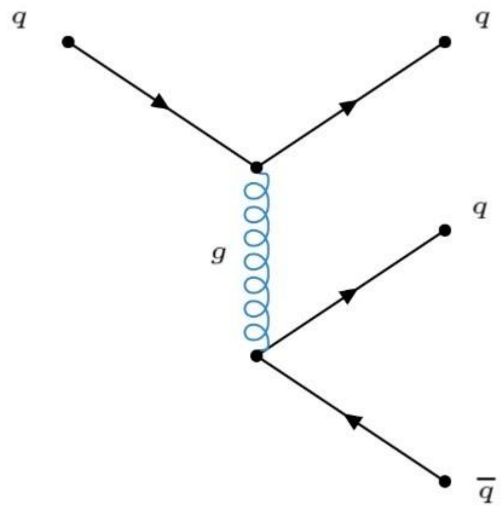

Fig. 2:

This figure shows the quark-antiquark pair production strong process in an electron proton deep inelastic scattering experiment. Since the gluon is suppressed by the $1/q^2$ gluon propagator, the pair production is more likely to happen at low value of q. The momentum of the pair produced sea quarks is just the momentum of the virtual gluon, hence, a low q indicates a low impulse fraction x of the interacting sea quarks.

5. Conclusions

The resulting rotational frequency (2.179 kHz) of the main axis (and the rotation of the sea as a whole) fits exactly with the relation $mv^2/r = m^2G/r^2$, offering an indication for gravity even inside a nucleon. Considering the fact that quarks fly around in all directions, this model is able to accurately explain why (only) two directions of the nucleon's spin exist. The relation [3] derived above identifies the major cause of the generation of sea quarks, whereas the release of the Coulomb energy between 4 destroyed, negatively and positively charged sea u- and d-(anti)quarks creates 4 new sea quarks/antiquarks. This relation can also explain the large mass of a nucleon: $m_n - E_{v,s,g} \approx \frac{137.035}{2} \cdot \left(m_u + m_d + \frac{E_{kin,s,g}}{c^2}\right)$. Therefore, we conclude that the released Coulomb energy between a short-term orbiting sea quark pair (and not only the strong interaction or vacuum fluctuations) is the major source of sea quark generation.

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