On the Quantum Mechanical State of the Δ^{++} Baryon

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The Δ^{++} and the Ω^- baryons have been used as the original reason for the construction of the Quantum Chromodynamics theory of Strong Interactions. The present analysis relies on the multiconfiguration structure of states which are made of several Dirac particles. It is shown that this property, together with the very strong spin-dependent interactions of quarks provide an acceptable explanation for the states of these baryons and remove the classical reason for the invention of color within Quantum Chromodynamics. This explanation is supported by several examples that show a Quantum Chromodynamics' inconsistency with experimental results. The same arguments provide an explanation for the problem called the proton spin crisis.

1 Introduction

It is well known that writing an atomic state as a sum of terms, each of which belongs to a specific configuration is a useful tool for calculating electronic properties of the system. This issue has already been recognized in the early days of quantum mechanics [1]. For this purpose, mathematical tools (called angular momentum algebra) have been developed mainly by Wigner and Racah [2]. Actual calculations have been carried out since the early days of electronic computers [3]. Many specific properties of atomic states have been proven by these calculations. In particular, these calculations have replaced guesses and conjectures concerning the mathematical form of atomic states by evidence based on a solid mathematical basis. In this work, a special emphasis is given to the following issue: Contrary to a naive expectation, even the ground state of a simple atom is written as a sum of more than one configuration. Thus, the apparently quite simple closed shell ground state of the two electron He atom, having $J^\pi = 0^+$, *disagrees* with the naive expectation where the two electrons are just in the $1s^2$ state. Indeed, other configurations where individual electrons take higher angular momentum states (like $1p^2$, $1d^2$, etc.) have a non-negligible part of the state's description [3]. The multiconfiguration description of the ground state of the He atom proves that shell model notation of state is far from being complete. Notation of this model can be regarded as an anchor configuration defining the J^π of the state. Therefore, all relevant configurations must have the same parity and their single-particle angular momentum must be coupled to the same J.

This paper discusses some significant elements of this scientific knowledge and explains its crucial role in a quantum mechanical description of the states of the Δ^{++}, the Δ^- and the Ω^- baryons. In particular, it is proved that these baryons do not require the introduction of new structures (like the $SU(3)$ color) into quantum mechanics. A by-product of this analysis is the settlement of the "proton spin crisis" problem.

The paper is organized as follows. The second section describes briefly some properties of angular momentum algebra. It is proved in the third section that ordinary laws of quantum mechanics explain why the states of the Δ^{++}, Δ^- and Ω^- baryons are consistent with the Pauli exclusion principle. This outcome is used in the fourth section for showing that QCD does not provide the right solution for hadronic states. The problem called "proton spin crisis" is explained in the fifth section. The last section contains concluding remarks.

2 Some Features of Angular Momentum Algebra

Consider the problem of a bound state of N Dirac particles. (Baryonic states are extremely relativistic. Therefore, a relativistic formulation is adopted from the beginning.) This system is described as an eigenfunction of the Hamiltonian. Thus, the time variable is removed and one obtains a problem of $3N$ spatial variables for each of the four components of a Dirac wave function. It is shown here how angular momentum algebra can be used for obtaining a dramatic simplification of the problem.

The required solution is constructed as a sum of terms, each of which depends on all the independent variables mentioned above. Now angular momentum is a good quantum number of a closed system and parity is a good quantum number for systems whose state is determined by strong or electromagnetic interactions. Thus, one takes advantage of this fact and uses only terms that have the required angular momentum and parity, denoted by J^π. (Later, the lower case j^π denotes properties of a bound spin-1/2 single particle.)

The next step is to write each term as a product of N single particle Dirac functions, each of which has a well defined angular momentum and parity. The upper and lower parts of a Dirac function have opposite parity [4, see p. 53]. The angular coordinates of the two upper components of the Dirac function have angular momentum l and they are coupled with the spin to an overall angular momentum $j = l \pm 1/2$ ($j > 0$). The two lower components have angular momentum $(l \pm 1) \geq 0$ and together with the spin, they are coupled to the same j. The spatial angular momentum eigenfunctions having an eignevalue l, make a set of $(2l + 1)$ members denoted by

$Y_{lm}(\theta,\phi)$, where θ, ϕ denote the angular coordinates and $-l \le m \le l$ [2].

It is shown below how configurations can be used for describing a required state whose parity and overall spin are known.

3 The Δ^{++} State

The purpose of this section is to describe how the state of each of the four Δ baryons can be constructed in a way that abides by ordinary quantum mechanics of a system of three fermions. Since the $\Delta^{++}(1232)$ baryon has 3 valence quarks of the u flavor, the isospin $I = 3/2$ of all four Δ baryons is fully symmetric. Therefore, the space-spin components of the 3-particle terms must be antisymmetric. (An example of relevant nuclear states is presented at the end of this section.) Obviously, each of the 3-particle terms must have a total spin $J = 3/2$ and an even parity. For writing down wave functions of this kind, single particle wave functions having a definite j^π and appropriate radial functions are used. A product of n specific j^π functions is called a configuration and the total wave function takes the form of a sum of terms, each of which is associated with a configuration. Here n=3 and only even parity configurations are used. Angular momentum algebra is applied to the single particle wave functions and yields an overall $J = 3/2$ state. In each configuration, every pair of the Δ^{++} u quarks must be coupled to an antisymmetric state. r_j denotes the radial coordinate of the jth quark.

Each of the A-D cases described below contains one configuration and one or several antisymmetric 3-particle terms. The radial functions of these examples are adapted to each case.

Notation: $f_i(r_j)$, $g_i(r_j)$, $h_i(r_j)$ and $v_i(r_j)$ denote radial functions of Dirac single particle $1/2^+$, $1/2^-$, $3/2^-$ and $3/2^+$ states, respectively. The index i denotes the excitation level of these functions. Each of these radial functions is a two-component function, one for the upper 2-component spin and the other for the lower 2-component spin that belong to a 4-component Dirac spinor.

A. In the first example all three particles have the same j^π,

$$f_0(r_0)\,f_1(r_1)\,f_2(r_2)\;1/2^+\;1/2^+\;1/2^+. \tag{1}$$

Here the spin part is fully symmetric and yields a total spin of 3/2. The spatial state is fully antisymmetric. It is obtained from the 6 permutations of the three orthogonal $f_i(r_j)$ functions divided by $\sqrt{6}$. This configuration is regarded as the anchor configuration of the state.

B. A different combination of $j_i = 1/2$ can be used,

$$f_0(r_0)g_0(r_1)g_1(r_2)\;1/2^+\;1/2^-\;1/2^-. \tag{2}$$

Here, the two single particle $1/2^-$ spin states are coupled symmetrically to j=1 and they have two orthogonal radial functions g_i. The full expression can be antisymmetrized.

C. In this example, just one single particle is in an angular excitation state,

$$f_0(r_0)\,f_0(r_1)v_0(r_2)\;1/2^+\;1/2^+\;3/2^+. \tag{3}$$

Here we have two $1/2^+$ single particle functions having the same non-excited radial function. These spins are coupled antisymmetrically to a spin zero two particle state. These spins have the same non-excited radial function. The third particle yields the total $J = 3/2$ state. The full expression can be antisymmetrized.

D. Here all the three single particle j^π states take different values. Therefore, the radial functions are free to take the lowest level,

$$f_0(r_0)g_0(r_1)h_0(r_2)\;1/2^+\;1/2^-\;3/2^-. \tag{4}$$

Due to the different single particle spins, the antisymmetrization task of the spin coordinates can easily be done. (The spins can be coupled to a total $J = 3/2$ state in two different ways. Hence, two different terms belong to this configuration.)

The examples A-D show how a Hilbert space basis for the $J^\pi = 3/2^+$ state can be constructed for three identical fermions. Obviously, more configurations can be added and the problem can be solved by ordinary spectroscopic methods. It should be noted that unlike atomic states, the very strong spin dependent interactions of hadrons are expected to yield a higher configuration mixture.

It is interesting to note that a similar situation is found in nuclear physics. Like the u,d quarks, the proton and the neutron are spin-1/2 fermions belonging to an isospin doublet. This is the basis for the common symmetry of isospin states described below. Table 1 shows energy levels of each of the four A=31 nuclei examined [5, see p. 357]. Each of these nuclei has 14 protons and 14 neutrons that occupy a set of inner closed shells and three nucleons outside these shells. (The closed shells are $1/2^+$, $3/2^-$, $1/2^-$, and $5/2^+$. The next shells are the $1/2^+$ that can take 2 nucleons of each type and the

Table 1: Nuclear A=31 Isospin State Energy levels (MeV)

J^π	I (T)[a]	^{31}Si	^{31}P	^{31}S	^{31}Cl[b]
$1/2^+$	1/2	—	0	0	—
$3/2^+$	3/2	0	6.38	6.27	0
$1/2^+$	3/2	0.75	7.14	7.00	—

[a] I,T denote isospin in particle physics and nuclear physics, respectively.
[b] The ^{31}Cl data is taken from [6].

$3/2^+$ shell that is higher than the $1/2^+$ shell. [7, See p. 245]. The state is characterized by these three nucleons that define the values of total spin, parity and isospin. The first line of table 1 contains data of the ground states of the $I = 1/2$ ^{31}P and ^{31}S nuclei. The second line contains data of the lowest level of the $I = 3/2$ state of the four nuclei. The quite small energy difference between the ^{31}P and ^{31}S excited states illustrates the quite good accuracy of the isospin approximation. The third line of the table shows the first excited $I = 3/2$ state of each of the four nuclei. The gap between states of the third and the second lines is nearly, but not precisely, the same. It provides another example of the relative goodness of the isospin approximation.

The nuclear states described in the first and the second lines of table 1 are relevant to the nucleons and the Δ baryons of particle physics. Indeed, the states of both systems are characterized by three fermions that may belong to two different kinds and where isospin is a useful quantum number. Here the neutron and the proton correspond to the ground state of ^{31}P and ^{31}S, respectively, whereas energy states of the second line of the table correspond to the four Δ baryons. Every nuclear energy state of table 1 has a corresponding baryon that has the same spin, parity, isospin and the I_z isospin component. Obviously, the dynamics of the nuclear energy levels is completely different from hadronic dynamics. Indeed, the nucleons are composite spin-1/2 particles whose state is determined by the strong nuclear force. This is a residual force characterized by a rapidly decaying attractive force at the vicinity of the nucleon size and a strong repulsive force at a smaller distance [7, see p. 97]. On the other hand, the baryonic quarks are elementary pointlike spin-1/2 particles whose dynamics differs completely from that of the strong nuclear force. However, both systems are made of fermions and the spin, parity and isospin analogy demonstrates that *the two systems have the same internal symmetry.*

The following property of the second line of table 1 is interesting and important. Thus, all nuclear states of this line have the same *symmetric* $I = 3/2$ state. Hence, due to the Pauli exclusion principle, all of them have the same *antisymmetric space-spin state.* Now, for the ^{31}P and ^{31}S nuclei, this state is an excited state because they have lower states having $I = 1/2$. However, the ^{31}Si and ^{31}Cl nuclei have no $I = 1/2$ state, because their $I_z = 3/2$. Hence, the second line of table 1 shows *the ground state of the* $I_z = 3/2$ *nuclei*. It will be shown later that this conclusion is crucial for having a good understanding of an analogous quark system. Therefore it is called *Conclusion A*.

Now, the ^{31}Si has three neutrons outside the 28 nucleon closed shells and the ^{31}Cl has three protons outside these shells. Hence, the outer shell of these two nuclear states consists of three identical fermions which make the required ground state. Relying on this nuclear physics example, one deduces that *the Pauli exclusion principle is completely consistent with three identical fermions in a* $J^\pi = 3/2^+$ *and* $I = 3/2$ *ground state.* The data of table 1 are well known in nuclear physics.

A last remark should be made before the end of this section. As explained in the next section, everything said above on the isospin quartet $J^\pi = 3/2^+$ states of the three *ud* quark flavor that make the four Δ baryons, holds for the full decuplet of the three *uds* quarks, where, for example, the Ω^- state is determined by the three *sss* quarks. In particular, like the Δ^{++} and the Δ^-, *the* Ω^- *baryon is the ground state of the three sss quarks and each of the baryons of the decuplet has an antisymmetric space-spin wave function.*

4 Discussion

It is mentioned above that spin-dependent interactions are much stronger in hadronic states than in electronic states. This point is illustrated by a comparison of the singlet and triplet states of the positronium [8] with the π^0 and ρ^0 mesons [9]. The data are given in table 2. The fourth column of the table shows energy difference between each of the $J^\pi = 1^-$ states and the corresponding $J^\pi = 0^-$ state. The last column shows the ratio between this difference and the energy of the $J^\pi = 0^-$ state.

Both electrons and quarks are spin-1/2 pointlike particles. The values of the last column demonstrate a clear difference between electrically charged electrons and quarks that participate in strong interactions. Indeed, the split between the two electronic states is *very small*. This is the reason for the notation of *fine structure* for the spin dependent split between electronic states of the same excitation level [10, see p. 225]. Table 2 shows that the corresponding situation in quark systems is larger by more than 9 orders of magnitude. Hence, spin dependent interactions in hadrons are very strong and make an important contribution to the state's energy.

Now, electronic systems in atoms satisfy the Hund's rules [10, see p. 226]. This rule says that in a configuration, the state having the highest spin is bound stronger. Using this rule *and* the very strong spin-dependent hadronic interaction which is demonstrated in the last column of table 2, one con-

Table 2: Positronium and meson energy (MeV)

Particle	J^π	Mass	$M(1^-) - M(0^-)$	$\Delta M/M(0^-)$
e^+e^-	0^-	~ 1.022	—	—
e^+e^-	1^-	~ 1.022	8.4×10^{-10}	8.2×10^{-10}
π^0	0^-	135	—	—
ρ^0	1^-	775	640	4.7

cludes that the anchor configuration A of the previous section really describes a very strongly bound state of the Δ^{++} baryon. In particular, the isospin doublet $J^\pi = 1/2^+$ state of the neutron and the proton correspond to the same $J^\pi = 1/2^+$ of the ground state of the $A = 31$ nuclei displayed in the first line of table 1. The isospin quartet of the Δ baryons correspond to the isospin quartet of the four nuclear states displayed in the second line of table 1.

Here the significance of Conclusion A of the previous section becomes clear. Indeed, an analogy is found between the two nuclear states of the $I = 3/2$ and $I_z = \pm 1/2$, namely the ^{31}P and the ^{31}S are *excited states* of these nuclei whereas the $I = 3/2$ and $I_z = \pm 3/2$, namely the ^{31}Si and the ^{31}Cl states are the *ground states* of these nuclei. The same pattern is found in the particle physics analogue. The Δ^+ and the Δ^0 are *excited states* of the proton and the neutron, respectively. This statement relies on the fact that both the proton and the Δ^+ states are determined by the *uud* quarks. Similarly, the neutron and the Δ^0 states are determined by the *udd* quarks. On the other hand, in the case of the ^{31}Si and the ^{31}Cl nuclei, the $I = 3/2$ and $J^\pi = 3/2^+$ states are the *ground states* of these nuclei. The same property holds for the Δ^{++} and the Δ^-, which are the *ground states* of the *uuu* and *ddd* quark systems, respectively.

The relationship between members of the lowest energy $J^\pi = 1/2^+$ baryonic octet and members of the $J^\pi = 3/2^+$ baryonic decuplet can be described as follows. There are 7 members of the decuplet that are excited states of corresponding members of the octet. Members of each pair are made of the same specific combination of the *uds* quarks. The Δ^{++}, Δ^- and Ω^- baryons have no counterpart in the octet. Thus, in spite of being a part of the decuplet whose members have space-spin antisymmetric states, these three baryons are the *ground state* of the *uuu, ddd* and *sss* quarks, respectively.

This discussion can be concluded by the following statements: *The well known laws of quantum mechanics of identical fermions provide an interpretation of the Δ^{++}, Δ^- and Ω^- baryons, whose state is characterized by three uuu, ddd and sss quarks, respectively. There is no need for any fundamental change in physics in general and for the invention of color in particular. Like all members of the decuplet, the states of these baryons abide by the Pauli exclusion principle.* Hence, one wonders why particle physics textbooks regard precisely the same situation of the four Δ baryons as a fiasco of the Fermi-Dirac statistics [11, see p. 5].

The historic reasons for the QCD creation are the states of the Δ^{++} and the Ω^- baryons. These baryons, each of which has three quarks of the same flavor, are regarded as the *classical reason* for the QCD invention [12, see p. 338]. The analysis presented above shows that this argument does not hold water. For this reason, one wonders whether QCD is really a correct theory. This point is supported by the following examples which show that QCD is inconsistent with experimental results.

1. The interaction of hard real photons with a proton is practically the same as its interaction with a neutron [13]. This effect cannot be explained by the photon interaction with the nucleons' charge constituents, because these constituents take different values for the proton and the neutron. The attempt to recruit Vector Meson Dominance (VMD) for providing an explanation is unacceptable. Indeed, Wigner's analysis of the irreducible representations of the Poincare group [14] and [15, pp. 44–53] proves that VMD, which mixes a massive meson with a massless photon, is incompatible with Special relativity. Other reasons of this kind also have been published [16].
2. QCD experts have predicted the existence of strongly bound pentaquarks [17, 18]. In spite of a long search, the existence of pentaquarks has not been confirmed [19]. By contrast, correct physical ideas used for predicting genuine particles, like the positron and the Ω^-, have been validated by experiment after very few years (and with a technology which is very very poor with respect to that used in contemporary facilities).
3. QCD experts have predicted the existence of chunks of Strange Quark Matter (SQM) [20]. In spite of a long search, the existence of SQM has not been confirmed [21].
4. QCD experts have predicted the existence of glueballs [22]. In spite of a long search, the existence of glueballs has not been confirmed [9].
5. For a very high energy, the proton-proton (*pp*) total and elastic cross section increase with collision energy [9] and the ratio of the elastic cross section to the total cross section is nearly a constant which equals about 1/6. This relationship between the *pp* cross sections is completely different from the high energy electron-proton (*ep*) scattering data where the total cross section decreases for an increasing collision energy and the elastic cross section's portion becomes negligible [23]. This effect proves that the proton contains a quite solid component that can take the heavy blow of the high energy collision and keep the entire proton intact. This object cannot be a quark, because in energetic *ep* scattering, the electron strikes a single quark and the relative part of elastic events is negligible. QCD has no explanation for the *pp* cross section data [24].

5 The Proton Spin Crisis

Another problem which is settled by the physical evidence described above is called *the proton spin crisis* [25, 26]. Here polarized muons have been scattered by polarized protons. The results prove that the instantaneous quark spin sums up to a very small portion of the entire proton's spin. This outcome, which has been regarded as a surprise [26], was later supported by other experiments. The following lines contain a straightforward explanation of this phenomenon.

The four configurations A-D that are a part of the Hilbert space of the Δ^{++} baryon are used as an illustration of the problem. Thus, in configuration A, all single particle spins are parallel to the overall spin. The situation in configuration B is different. Here the single particle function $j^\pi = 1/2^-$ is a coupling of $l = 1$ and $s = 1/2$. This single particle coupling has two terms whose numerical values are called Clebsh-Gordan coefficients [2]. In one of the coupling terms, the spin is parallel to the overall single particle angular momentum and in the other term it is antiparallel to it. This is an example of an internal partial cancellation of the contribution of the single particle spin to the overall angular momentum. (As a matter of fact, this argument also holds for the lower pair of components of each of Dirac spinor of configuration A. Here the lower pair of the high relativistic system is quite large and it is made of $l = 1$ $s = 1/2$ coupled to $J = 1/2$.) In configuration C one finds the same effect. Spins of the first and the second particles are coupled to $j_{01} = 0$ and cancel each other. In the third particle the $l = 2$ spatial angular momentum is coupled with the spin to $j = 3/2$. Here one also finds two terms and the contribution of their single-particle spin-1/2 partially cancels. The same conclusion is obtained from an analogous analysis of the spins of configuration D.

It should be pointed out that the very large hadronic spin-dependent interaction which is demonstrated by the data of table 2, proves that in hadronic states, one needs many configurations in order to construct a useful basis for the Hilbert space of a baryon. It follows that in hadrons the internal single particle cancellation seen in configurations of the previous section, is expected to be quite large.

Obviously, the configuration structure of the proton relies on the same principles. Here too, many configurations, each of which has the quantum numbers $J^\pi = 1/2^+$, are needed for the Hilbert space. Thus, a large single particle spin cancellation is obtained. Therefore, the result of [25] is obvious. It should make neither a crisis nor a surprise.

On top of what is said above, the following argument indicates that the situation is more complicated and the number of meaningful configurations is even larger. Indeed, it has been shown that beside the three valence quarks, the proton contains additional quark-antiquark pair(s) whose probability is about 1/2 pair [23, see p. 282]. It is very reasonable to assume that all baryons share this property. The additional quark-antiquark pair(s) increase the number of useful configurations and of their effect on the Δ^{++} ground state and on the proton spin as well.

6 Concluding Remarks

Relying on the analysis of the apparently quite simple ground state of the He atomic structure [3], it is argued here that *many* configurations are needed for describing a quantum mechanical state of more than one Dirac particle. This effect is much stronger in baryons. where, as shown in table 2, spin-dependent strong interactions are very strong indeed. This effect and the multiconfiguration basis of hadronic states do explain the isospin quartet of the $J = 3/2^+$ Δ baryons. Here the Δ^0 and the Δ^+ are *excited states* of the neutron and the proton, respectively whereas their isospin counterparts, the Δ^{++} and the Δ^- are *ground states* of the *uuu* and the *ddd* quark systems, respectively. Analogous conclusions hold for all members of the $J = 3/2^+$ baryonic decuplet that includes the Ω^- baryon. It is also shown that states of four $A = 31$ nuclei are analogous to the nucleons and the Δs isospin quartet (see table 1).

The discussion presented above shows that there is no need for introducing a new degree of freedom (like color) in order to settle the states of Δ^{++}, Δ^- and Ω^- baryons with the Pauli exclusion principle. Hence, there is no reason for the QCD invention. Several inconsistencies of QCD with experimental data support this conclusion.

Another aspect of recognizing implications of the multiconfiguration structure of hadrons is that the proton spin crisis experiment, which shows that instantaneous spins of quarks make a little contribution to the proton's spin [25], creates neither a surprise nor a crisis.

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