The Energy Spectra of Cosmic Ray Protons, the Origin of Gluons, and the Mechanism of Baryon Generation

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For the past sixty years, the generation of hadrons has been dealt with through a framework of theories devised to describe the so-called Strong interactions. About two years ago, the author put forward an essentially quantum electrodynamical model for the same purpose. The present paper contains the latest development in the interpretation of those results, and we reached a point where a bridge can be extended to existing theories. The main result of our previous work has been the determination of an energetic interval of 2.7 GeV between a "vacuum" parent state and the proton rest-energy. The full interpretation of this finding is that this is the energy advantage (calculated from a Regularization procedure) that stabilizes charge (the baryons) confined in the shape of loops by correlating EM excitations at 3.7 GeV. That is, we have been able to establish that these EM excitations are in fact the Gluons of high-energy physics, and they come straight from relativistic quantum electrodynamics through the Regularization procedure of loop energies. The value 2.7 GeV obtained from Regularization is of the correct magnitude to explain the difference between the strength of Strong and EM interactions (15 versus 1/137). The size of a proton can also be approximately deduced from our arguments.

1 Introduction

The present paper contains the main results of investigations which have directly addressed the long-standing problem of describing the genesis of particles. In particular, the issue of the origin of mass is considered [1, 2]. Many of the ideas and concepts in this work have previously been advanced by Barut [3], Bostick [4], and Jehle [5]. In particular, the starting point in this treatment, is that magnetic moments are fundamental properties of leptons and baryons, and that the presence of magnetic moments in particles can be modelled by the introduction of an intrinsic closed electrical current loop of finite (rather than point-like) size. It might be argued that such hypothesis should be incompatible with QED and that electrons behave experimentally as point-like objects. However, the present treatment may be regarded as describing the earliest stages of a particle condensation process taking place in an extremely dense medium at 10^{13} K. Present day experiments take place under completely different conditions.

The current-loop model refers more properly to the EM fields in this *embryonic* stage, and no specific mass/charge distribution for baryons is explicitly needed or introduced. A blend of fermion/EM fields in loop form act to correlate and confine baryon fields inside the loop. A multiply-connected current path should arise, whose possible topological forms were the object of intense discussions by Bostick and Jehle, but in the absence of more concrete evidence a simple circular loop path is adopted in this treatment. The confinement of magnetic flux within such paths was initially [1] assumed as occurring in numbers of flux quanta determined by the magnetic moments in magneton units, a property easily derived from Barut's semiclassical spinning particle-model, but such assumption is later adjusted to better fit data.

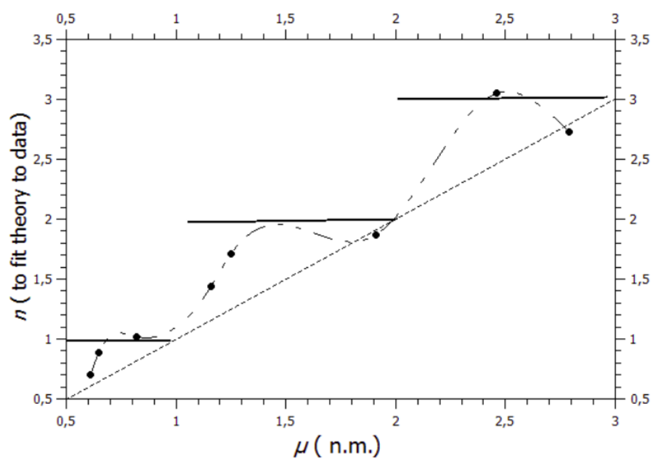

Fig. 1: Plot of n against the magnetic moment for the baryons octet (points) from the definition $n = (2c^2\alpha/e^3)\,\mu\, m$. The diagonal line is the classical prediction of one flux quantum per nuclear magneton (n.m.). Nucleons are on the line. The data display undulations, and a tendency to reach for the steps (traced line as guide) [2].

In paper [1], we have shown that it is possible to describe the masses m of all the baryons of the octet and decuplet in terms of a single formula, involving the magnetic moments μ and corresponding numbers of confined flux quanta n. One might otherwise use this relation to define n from the experimental masses and moments [2]:

$$n = \left(2fc^2\alpha/e^3\right)\mu\, m$$

where $f = 1$ for spin 1/2 and $\approx 1/\sqrt{3}$ for spin 3/2, and α is the fine-structure constant (one immediately recovers the often-mentioned inverse relation of mass with the constant α, since n and μ are approximately proportional to each other). The treatment that produces this equation is essentially heuristic, but precise enough for instance to highlight the dependence of mass upon the square-root of the spin angular momentum, as reported in the literature (note that the phenomenological factor f that corrects for spin is related to kinetic energies rather than to magnetic constributions) (cf. Fig. 1 of [1]).

In paper [2], whose main results are reproduced in the following section for the sake of clarity, we took much further the treatment presented in [1]. A key parameter in this analysis is the number of flux quanta n arrested inside a current loop. In particular, we obtain in [2] a very revealing result which has previously been reported mainly through Condensed Matter physics investigations, which is that the energy of currents (here regarded as a particle's rest mass) is a *periodic function* of the confined magnetic flux in multiply-connected structures. Consistently with these results from Condensed Matter systems, the periodic dependence of baryons masses (and confined flux) with the magnetic moments (see Fig. 1) can be regarded as a demonstration that the initial hypotheses of the present investigations are sound. That is, indeed mass is a manifestation of magnetodynamic energies (related to currents) confined in a multiply-connected region. Such hypothesis is therefore consistent with experimental data. With this evidence in hand, the next step clearly was to advance beyond the initial phenomenological-heuristic argumentation and propose a field-theoretical treatment that would describe the observed mass-energy relations for actual particles.

Such kind of treatment has previously been applied for fermion fields flowing around a closed loop containing magnetic flux (see references in [2]). Starting from a Lagrangian suitable to these fields (assumed as built upon a proton "substrate", following Barut), we then obtain an energy spectrum for the possible traveling wave-states around a closed path. To simulate the perturbations coming from the vacuum background which will be added to the proton state, a sum over the states in the energy spectrum of kinetic energies for the EM/fermion quasiparticles is necessary. An Epstein-Riemann Zeta function Regularization procedure previously adopted for the Casimir Effect problem is applied to eliminate divergences when the sum over the energy spectrum states is carried out, and the periodic behavior of the baryon masses with magnetic flux is quantitatively reproduced with no further forms of energies required besides the magnetodynamic terms. A new result of this treatment [2], is the prediction of a parent state at $U_0 = 3.7$ GeV, which should be identified with a dense medium (opposite to what we usually qualify as "vacuum"), whose fluctuation instabilities would give origin to baryons. The present work goes beyond [2] in the search for evidence for the existence of this state as well as the source of the correlations. The calculated value of U_0 immediately indicates that protons (of rest mass 0.94 GeV) should become unstable if accelerated to kinetic energies beyond 2.7 GeV if their structure were not strong enough and capable to radiate excess energy. We found out that a very good way to investigate this point is through the analysis of the spectra of protons in cosmic rays, whose energy flux profile peaks at 2.7 GeV kinetic energy (Fig. 3 below) for reasons we will discuss.

In the following sections, we firstly present the field-theoretical model introduced in [2], alongside the comparison with experimental data for mass and magnetic moments for baryons. In the analysis in Section 3, we test the hypothesis of the existence of an energy level for vacuum by examining data collected for protons in cosmic rays and discuss the relation between this energy level and gluons. In Section 4, we show that an estimate for the proton size can be obtained from the theory.

2 Field-theoretical model for generation of baryons

For the developments that led to this field-theoretical treatment, we make reference also to the *Annales* paper [1] (see also references therein and in [2]). Let's consider a fermion field confined by EM energy inside a circular path of length L, enclosing an amount of self induced magnetic flux φ, in a potential A. We need to show that such an EM/fermion packet corresponds to a state detached from a higher state associated with a sea of excitations in equilibrium, and therefore might be used to represent a "quasiparticle". The relativistic Lagrangian for such an object can be modelled through the dressing of a proton of mass m_p (as once proposed by A. Barut) in view of the presence of magnetodynamic terms [2]:

$$L = \overline{\Psi} \left\{ i\alpha_\mu \left(\hbar\partial_\mu - i\,\frac{\mathrm{e}}{\mathrm{c}}\, A_\mu \right) - \alpha_4\, m_p\, c \right\} \Psi \tag{1}$$

where the α_μ are Dirac matrices. This Lagrangian can readily be transformed into a Hamiltonian form. Assuming a constant potential A around the ring path, the spectrum of possible energies for a confined fermion becomes:

$$\epsilon_k = c\,\left\{ (p_k - eA/c)^2 + m_p^2\, c^2 \right\}^{1/2} \tag{2}$$

which comes straight from the orthonormalized definition of the Dirac matrices and diagonalization of the Hamiltonian. We now definitely impose a circular closed path. If one takes the Bohr-Sommerfeld quantization conditions, the field momentum p_k (for integer k) is quantized in discrete values $2\pi\,\hbar\,k/L$. We start from this assumption, but the true boundary conditions to close the wave loop might impose corrections to this rule in the form of a phase factor (a phase factor is introduced in the fit to the data in Fig.3 below). The potential A can be replaced by φ/L. Environmental (vacuum) fluctuation effects on the kinetic energy are accounted for in a way similar to that applied in the analysis of the Casimir Effect, by summing over all possible integer values of k in (2) [2]. This summation diverges. According to the theory of functions of a complex variable, the removal of such divergences requires that the analytic continuation of the terms be taken, which reveals the diverging parts which are thus considered as contributions from the infinite vacuum reservoir. What remains plays the important role of energetically stabilizing the loops (in a way that resembles the role of phonons in the formation of Cooper pairs). It is necessary to rewrite (2) in terms of Epstein-Riemann Zeta functions [2], including the summation over k from minus to plus infinity integers, and making a Regularization (Reg) transformation. Here $M(\varphi)$ is the flux-dependent dressed mass of a baryon, and $s \to -1$:

$$M c^2 = U_0 + \mathrm{Reg} \sum_k c \left\{(p_k - e\varphi/Lc)^2 + m_p^2 c^2\right\}^{-s/2} \quad (3)$$

where we have allowed for the existence of a finite energy U_0 to represent an hypothetical state from which the individual baryons would condense, since they would correspond to lower energy states. Such particles should be characterized as states of energy lower than U_0. It is convenient to define from L a parameter with units of mass $m_0 = 2\pi\hbar/cL$, which will be used to define a scale in the fit to the data. We notice that m_0 is related to the parameter L in the same way field theories regard mass as created from broken symmetries of fields, establishing a range for an otherwise boundless field distribution (e.g. as happens with the London penetration depth at the establishment of a superconductor state, which is related to an electromagnetic field "mass" by a similar expression). For convenience, we define the ratios $m' = m_p/m_0$ and $u_0 = U_0/m_p c^2$. For comparison with the data analysis in our previous work [2], we must introduce also the number of flux quanta n (integer or not) associated to φ, such that $n = \varphi/\varphi_0$. In terms of these parameters one may write (3) in the form:

$$M(n)/m_p = u_0 + (1/m')\,\mathrm{Reg} \sum_k \left\{(k-n)^2 + m'^2\right\}^{-s/2} . \quad (4)$$

In the analysis of data, the experimental values of M/m_p for baryons will be plotted against n. The sum on the right side of (4) is a particular case of an Epstein Zeta function $Z(s)$, and becomes a Riemann Zeta function, since the summation is over one parameter k only. The summation diverges but it can be analytically continued over the complex plane, since the Epstein Zeta function displays the property of reflection. It has been shown that after the application of reflection, the resulting sum is already regularized, with the divergences eliminated. The reflection formula is [2]:

$$\pi^{-\frac{s}{2}}\,\Gamma\left(\frac{s}{2}\right) Z(s) = \pi^{\frac{s-1}{2}}\,\Gamma\left(\frac{1-s}{2}\right) Z(1-s) . \quad (5)$$

This replaces the diverging $Z(s)$ straight away by the regularized $Z(1-s)$, which is a convergent sum (since $\Gamma(-1/2) = -2\sqrt{\pi}$ we see that the regularized sums are negative, like in the Casimir Effect solution). The Regularization of (4) is carried out as follows (note that $s \to -1$, and the "reflected" exponent $-(1-s)/2$ replaces $-s/2$ of (4)). $Z(1-s)$ is given as [2]:

$$\begin{aligned}
&\sum_k \left\{(k-n)^2 + m'^2\right\}^{-(1-s)/2} = \\
&\frac{2}{\Gamma\left(\frac{1-s}{2}\right)} \int_0^\infty t^{\frac{1-s}{2}-1} \left(\sum_k e^{-(k-n)^2 t - m'^2 t}\right) dt = \\
&\frac{2\sqrt{\pi}}{\Gamma\left(\frac{1-s}{2}\right)} \int_0^\infty t^{-\frac{s}{2}-1} \left(\sum_k e^{-2\pi i k n}\, e^{-\frac{\pi^2 k^2}{t} - m'^2 t}\right) dt = \\
&\frac{2\sqrt{\pi}}{\Gamma\left(\frac{1-s}{2}\right)} \left(\frac{\Gamma\left(-\frac{s}{2}\right)}{m'^{-s}} + 2\pi^{-s/2} \sum_{k/0} \left(\frac{k}{m'}\right)^{\frac{-s}{2}} K_{\frac{s}{2}}(2\pi m' k)\, e^{-2\pi i k n}\right)
\end{aligned} \quad (6)$$

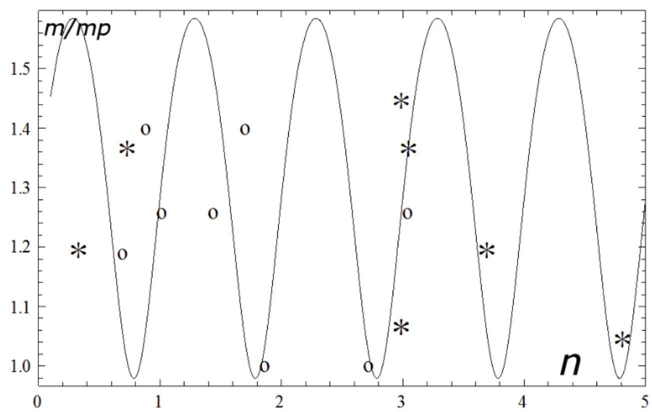

Fig. 2: Comparison of baryons masses calculated from (6) (line) as a function of confined flux n, with data points from Tables I and II of [2] for octet (open circles) and decuplet particles (m_t used [2], stars). Nucleons are on the basis of the figure. The points come from the heuristivc/phenomenological equation $n = (2c^2\alpha/e^3)\,\mu\, m$. The fit produces $U_0 = 3710$ MeV as the vacuum/environment parent level.

The "Reg" summation in (4) then becomes

$$\left(\pi^{\frac{2s-1}{2}} / \Gamma\left(\frac{s}{2}\right)\right) \Gamma\left(\frac{1-s}{2}\right) Z(1-s) ,$$

and the exponential produces a cosine term.

Since $\Gamma(-1/2) = -2\sqrt{\pi}$ we see that the regularized sum is negative, corresponding to energies lower than U_0. In the fitting to the data, we will admit that both m' and u_0 are adjustable parameters.

Fig. 2 shows the data for all baryons in Tables I and II of [2], and the plot of mass in (4) regularized by (6), for $u_0 = 3.96$ and $m' = 0.347$ (corresponding to $m_0 = 2.88\ m_p$ and $U_0 = 3710$ MeV). The energy 3710 MeV would represent the environment ("vacuum") energy (state) from which the baryons would evolve. By comparison with Yukawa's theory of the meson, one may interpret $m_0c^2 = 2710$ MeV as the mass of a particle that provides an internal correlation and keeps the dressed proton stable, a task usually attributed to gluons in particle theory. Such particle is essentially EM energy confined in a loop [4], and the correlated system would follow the behavior of an harmonic oscillator in resonance with the particle motion.

3 Evidence from the energy-flux profile of cosmic rays

This model produced an entirely new result, which is the proposal of a parent vacuum/environment energy state at 3.71 GeV. Flux profiles of cosmic ray (CR) protons display important features [6] that seem related to the existence of a "correlation" energy that keeps the loops dressing of protons, corresponding to the difference between 3.71 GeV and the proton's rest energy of 0.94 GeV.

It is worthwhile to examine some available experimental data, well gathered in [6]. Fig. 3 shows the energy flux profile of protons as detected from interstellar outer space by a space probe. The symmetry of this figure clearly gives an average energy per proton of about 2.7 GeV. Tsallis and collaborators [7] carried out the integration of a related set of data to obtain an averaged energy of about 2.88 GeV, with the comment "Any connection of this value with other cosmological or astrophysical quantities is of course very welcome". Statistical mechanics has several famous similar cases. For instance, in the Maxwell kinetic theory of velocities distribution in a gas, the average energy of a molecule matches the energy provided by the environment under equilibrium conditions, which is measured in terms of the absolute temperature as $3/2\,kT$. According to the theory in [2], in the case of the proton, equilibrium is reached against a vacuum at 3.7 GeV, which is 2.7 GeV higher in energy than the proton's rest energy, corresponding to a local temperature of about 10^{13} K. Therefore, the CR protons, similar to the classical gas case, display an averaged energy consistent with an equilibrium reached against the environment, at the predicted level at 3.7 GeV energy. It must be stressed that such equilibrium does not follow the classical formalism of Maxwell-Gibbs statistics, and requires relativistic effects to be included [7, 8].

4 About the size of the proton

The structure of fully developed protons is known to be formed by (the entanglement of) at least three major quark constituents, each of them with 1/3 of the proton rest mass (see topological considerations in [4, 5]), with charges of opposite signs. This is a very important detail, since the same external electric fields that accelerate the proton as a whole will stretch this structure with a similar force. Therefore, the proton can be regarded as a stressed/strained ensemble of charged objects strongly connected (entangled) together, and thus its elastic response behavior should be considered. Excited by external forces, a three-dimensional elastic structure will vibrate at its natural frequencies. The proton might be represented by a three-dimensional quantum harmonic oscillator. Following the considerations at the end of Section 2, we shall take 2.7 GeV as the ground state energy of an isolated oscillator [9]. This is the share of the 3.7 GeV that lays beyond the rest-energy. Extremely energetic quasiparticles from the original "vacuum" reservoir at 3.7 GeV would dress the proton fields leading to stabilization of the structure in the form of oscillators, in an energy state lower than the original "vacuum", establishing in this case the rest energy of a proton (in a way probably similar to how low-energy lattice phonons promote electron correlations and make the Cooper pairs stable in the superconductor ground state, which is lower in energy than the Fermi level by a small gap). This stable dressed-proton structure behaves like a vibrating system. The model developed in [2] and Section 2 actually deals with the fields of this correlations calculation. We now treat the elastic response of the particle in equilibrium with those fields.

The natural frequency of three-dimensional oscillations ω is given as: $3/2\,\hbar\omega = 2.7\,\text{GeV}$. One obtains $\omega = 2.7 \times 10^{24}$ rad/s, an extremely high figure, within the gamma-ray range of photons in the EM spectrum. What makes such oscillations regime stable?

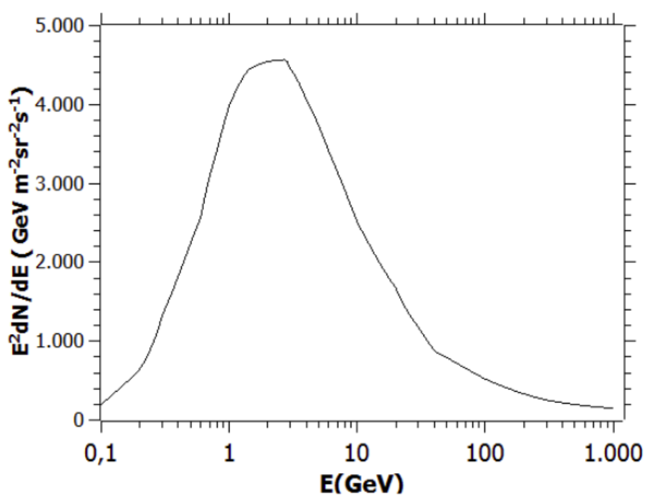

Fig. 3: Interstellar energy-flux profile of protons in CR, which peak at, and have an average energy of 2.7 GeV kinetic energy [3].

The diameter of a proton determined by scattering experiments is ≈ 1.8 fm. This should be taken as the maximum spacing between constituents in a "relaxed" proton structure, but such spacing is deformed by oscillations. Criteria have been developed to evaluate whether the deformation of interatomic spacing in a substance might provoke a change of state. A range of deformation between 5 and 10% of the relaxed "inter-constituent" spacing is usually recognized as within a typical limit for a structure to remain stable. The maximum possible oscillating displacement is

$$x_m = (2/3\ E/(m\omega^2))^{1/2}\,,$$

where E is 2.7 GeV. We obtain $x_m = 0.16$ fm, which is obtained independently of the knowledge of the proton size. In view of the stability criteria mentioned earlier, this would independently establish a proton size of at least 3 fm at 3.7 GeV conditions. When cooling took place, the structure shrunk to the measured 1.8 fm. One might even conjecture that the observed size of the proton cannot be smaller since smaller particles with same constituents simply break apart as soon as formed due to inelastic strains.

5 Conclusions

It is then possible to summarize all the results in this work: The observed size of the proton, 1.8 fm would be a consequence of its origins in an environment at about 3.7 GeV. According to the model, the particle condenses due to the provision of a 2.7 GeV correlation energy from fields confinement in the form of loops, as calculated by the Regularization procedure. These confined fields play the role of quasiparticles ("vacuum-dynamics" quasiparticles), which provide strongly-binding correlations, which join constituents like in a harmonic oscillator, promoting a stable structure. There is a clear potential association between these energetic quasiparticles and what is called gluons. The magnitude of 2.7 GeV is in a proportion consistent with the ratio of 15 to 1/137, to EM coupling energies, which is the accepted relation between Strong and EM interactions in the range of tenths of a femtometer.

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