The coherence length of the proton.

Osvaldo F. Schilling

Departamento de Física, Universidade Federal de Santa Catarina, 88040-900, Florianópolis, SC. Brazil.

Email: osvaldo.neto@ufsc.br

Abstract:

In recent work we have shown that the origin of baryons can be traced to electrodynamic instabilities of the vacuum, adopting the proton state as a substract ( as proposed by Barut, decades ago). As reported earlier, one might regard the proton state as separated from the vacuum by a 2.7 GeV energy difference ( loosely referred to as a "gap"). In this picture there is clear analogy between the origin of baryons and the electron-pairs condensation in normal-superconductor transitions, in which a true gap opens up from the Fermi Energy. In the present paper we demonstrate that the analogy does not stop there, since a "coherence length" for the inner constituents of the proton can indeed be defined and its existence experimentally found in the analysis of cosmic rays flux profiles. Such coherence length is on the order of 0.24 fm.

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**Introduction. Pippard´s coherence length in superconductors and an analogy with quantum oscillators**.

Let´s consider the superconductor case first. In search of improvements of the London theory of superconductivity, in 1953 Brian Pippard [1] introduced the concept that superconductor wavefunctions should have a limited extension, which we now recognize as the average range of entanglement between electrons in Cooper´s pairs, the "coherence length" $\xi$. Since the late 1930s London, as well as Slater( and possibly others), realized that in order to produce the rigidity of the momentum distribution of electrons in the superconductor phase, electrons should occupy a single state, which would therefore be detached by a gap from the Fermi level: close but beneath the top of electrons energy distribution in a crystal.

It was clear that the critical temperature $T_c$ should give a measure of the magnitude $\Delta$ of the gap, $kT_c = \Delta$.

The electrons in their detached level have a kinetic energy $E_c = p^2/2m$. The gap is small compared with the Fermi energy ( p is approximately the Fermi momentum $p_F$), so that one may write, $\Delta = \delta( E_c) = (p_F/m)\,\delta p$.

From the Uncertainty Principle, Pippard obtained an additional relation $\delta x\ \delta p \sim \hbar$, and thus introduced a correlation distance $\xi = \delta x$ , the "coherence length", along which the phases of wavefunctions should be correlated. With $kT_c = \Delta$ and introducing the Fermi velocity $v_F$, one obtains:

$$\xi = \frac{\hbar v_F}{kT_c} \tag{1}$$

Four years later the coherence length was definitely introduced through the BCS fieldtheoretical treatment of the superconductor transition.

The considerations above can be used to establish the following semiclassical analogy. Consider the Cooper pair as two masses linked by a rigid spring so that while separated from the equilibrium position by $\xi$ the gap energy imposes the maximum possible elastic energy:

$\Delta = ½\, m\omega^2\, \xi^2$ .

Here $\omega$ is the natural frequency of the spring. The quantity $\Delta$ should also give the maximum kinetic energy of vibrations $(p_F/m)\delta p$ . Applying the Uncertainty Principle as above, $\xi \times \delta p \approx$ cnst.$\times\, h$ , one obtains

$$\Delta = \text{cnst.}(\, h^2\, mc^2\, \omega^2/4)^{1/3} \tag{2}$$

The cubic-root term in this expression is the total energy of a *relativistic* harmonic oscillator in its ground state[2], in which we replace the term (cnst.) $mc^2$ inside the brackets for the Fermi Energy $p_F^2/2m$( the uncertainty relation is defined up to the attached cnst., of order 1 ~ 2 ). That is, the gap in the Cooper problem becomes the ground state energy of the relativistic quantum oscillator formed by the pair. The coherence length can be associated with the limiting elastic range of the vibrations $\xi$, and overcoming the gap and breaking the pair would be analogous to breaking the elastic regime.

In the following section we consider the reverse problem, I e, obtaining a gap and a coherence length from a harmonic oscillation problem.

## The proton coherence length

In recent years we have worked extensively on heuristic models for baryons, which resulted in three publications [3-5]. The main result of this work has been the realization that baryons should be the outcome of a process of stabilization( or condensation) of vortices of charge, generated from a parent state located at 3.7 GeV[3]. Such latter state might be associated with the EM vacuum and the baryons would come as a result of instabilities of EM origin taking place in that vacuum. Support for such an explanation comes from the energy distribution of protons and other particles in cosmic rays (CR)[6], which peak in the range 2.5-4 GeV, indicating a concentration of particles below the peak energy( see Figures 1 and 2, taken from [6]). As we show below the association of the peak position with the limiting "elastic" strength of a vortex of charge can be done from simple arguments, as well as it is possible to show that at the 3.7 GeV level some form of phase transition (melting ) might indeed happen as energy increases.

At some point in their history, particles in CR were subject to extreme electric and magnetic forces, and the measured flux distributions we detect now were established under the influence of such forces. Let´s concentrate on the case of protons, which represent by far the majority of the contents of CR. After their condensation in vortex form, a process of entanglement appears to take place resulting in a structure of extreme stability and strength( Note that the theory in [3] does not address how this entanglement process succeeds the initial vortex-stage). Stabilized protons are then composed of entangled constituents of different charge values, and probably different topological properties associated with these charge values[7]. Under extreme electromagnetic forces, the proton structure is subject to huge internal stresses. We now argue that the observed peak at 3GeV energy in the spectra of CR directly probes the proton structure elastic response to such forces. In what follows the reader will certainly recognize the similarities with the discussion in the initial section about Cooper pairs

It is well known that a spring-mass oscillating system of mass *m* and elastic spring constant *k* will spontaneously oscillate at its fundamental frequency

$\omega = (k/m)^{1/2}$ when subject to a constant force $F$ along the spring- mass direction. Let´s assume that the peak kinetic energy of 3 GeV corresponds to the ground state energy of a 3DIM quantum harmonic oscillator, so that $3/2\hbar\omega \approx 3$ GeV.

The proton has three main ( heavier) constituents of mass ~ $m/3$, with $m$ the proton mass. From classical mechanics there would be several natural modes of vibration and torsion. We take a representative natural frequency of this structure from the formula $\hbar\omega = \hbar\,(3k/m)^{1/2} = 2$ GeV= $3.2\text{x}\ 10^{-10}$ J, giving $\omega = 3.1\text{x}10^{24}$ rad/s ( we recognize that since the proton is a multi-component system other normal modes theoretically exist, but we will concentrate on the most conspicuous one, that at about 3 GeV).

The intense forces mentioned in the previous paragraphs would excite the vibration mode of frequency $\omega$, and the internal consituents of the proton would acquire additional oscillating displacements as a result. The maximum amplitude $\delta$ related to such additional oscilating motion is given by the maximum elastic energy expression:

$$3/2\,(m/3)\omega^2\delta^2 = 3/2\,\hbar\omega \tag{3}$$

One obtains $\delta = 2.4\text{x}10^{-16}$ m = 0.24 fm. This is the magnitude of the vibrational displacements( here considered elastic) of the proton inner constituents when excited 3 GeV above the rest state( compare with the discussion leading to eq. (2) above).

It remains to be discussed whether the elastic regime is still applicable, since this might imply the possibility of destruction of the structure. The value for $\delta$ is indeed deeply revealing as far as the process taking place at 3.7 GeV is concerned, as we discuss below.

**Analysis**

As argued in ref. [3], protons of energy around 3 GeV in theory reach their stability limits and lose the energy advantage over the parent state at 3.7 GeV. One might speculate that the proton would then “melt” into its parent phase.

From eq (3) we have calculated the value for the displacements $\delta$, which will be used to put such rather abstract concept of melting into a quantitative form. A practical way of doing this is through the Lindemann criterion ( LC) for the melting of a solid.

According to the LC a solid loses cohesion towards a disordered ( "molten") phase when atomic oscillations reach about 5 to 10% of the interatomic distance. Here we must replace the term interatomic by "inter-constituent" spacings. One might immediately evaluate if this is the case with the protons in CR. The radius of a proton is estimated from about 0.6 fm ( from the calculated profile of charge distribution) up to 0.9 fm obtained from scattering experiments. The inter-constituent spacing cannot be greater than the size of the particle itself, of 1.2 to 1.8 fm It is possible to conclude then that the amplitude $\delta$ = 0.24 fm is about 13 to 20 % of the accepted inter-constituent spacing. The Lindemann criterion for melting( if applicable in its usual form here) is therefore just exceeded at such high kinetic energies.

From the discussion in the initial section one might go half way around and come back, that is, begin from a quantum oscilator picture and come back to the concepts of gap energy and coherence. The parameter $\delta$ of 0.24 fm represents the coherence length of the constuents which together form a proton. The gap $\Delta$ is the 3 GeV energy , already predicied in [3]( see Figures 1 and 2).

There exists ample evidence that protons profusely radiate electromagnetic energy as their speed increases in accellerators, so that energy is released, thus avoiding breakdown( decay!). This is widely explored in synchrotron accellerators. Rather than decaying, protons and electrons radiate until strains come back to the full elastic regime and the structure is stable. This results in about 90% of cosmic rays particles displaying energies below 3 GeV( Figure 2).

One might conjecture that only electrons and protons are stable because nature provided only these two particles with a structure strong enough to resist the extreme stresses after their condensation from the 3.7 GeV parent level in the form of vortices[3]. All other observed baryons, mesons, etc, have extremely short mean lives, and correspondingly do have rest masses which approach 3 MeV, which leaves very little room for any kind of instability. Since we know about the electromagnetic fields from their interactions with particles and the observed radiation, another conclusion might be that electrodynamics follows Maxwell laws since these protons and electrons managed to retain structural integrity by radiating energy at a suitable rate, which happens to be that rate calculated from Maxwell electrodynamics. Particles following other sets of laws disappeared very fast and we have no trace of which laws might have been followed by them.

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Figure 1: Energy-flux profile of intergallactic protons, which peaks at 2.7 GeV[6].

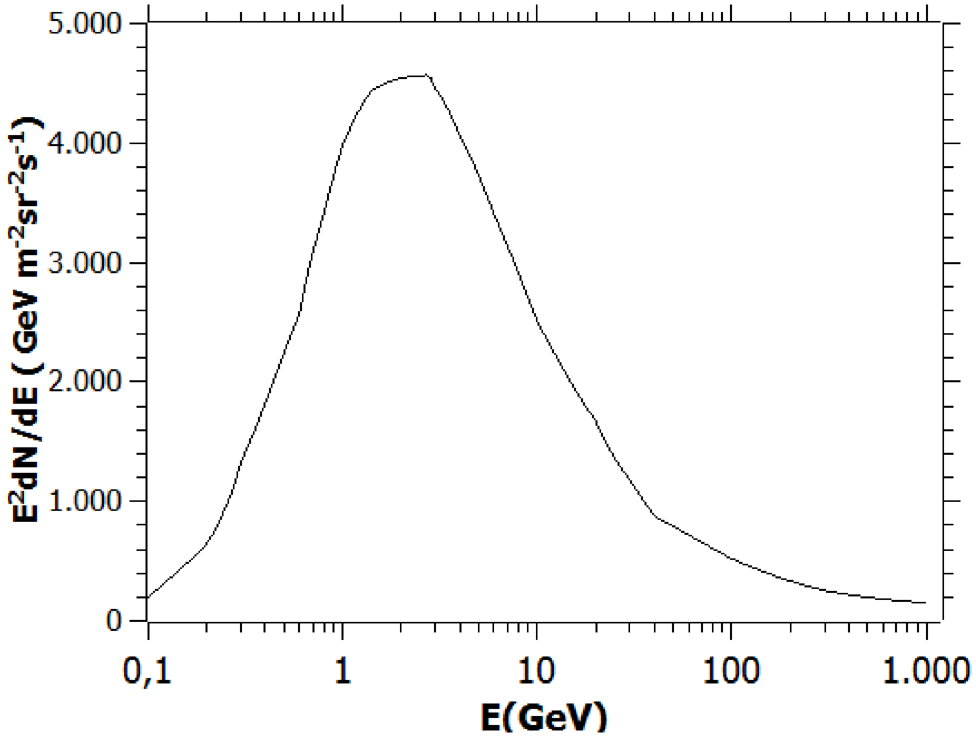


Figure 2: The previous figure is replotted. The curve below can be perfectly fitted by a Weibull distribution, which is usually associated with statistics of failure events. Integration shows 92% of protons below 3 GeV energy.