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OF THE NUCLEON**

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ON THE INTRINSIC CHARM COMPONENT OF THE NUCLEON

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Abstract: Using a \bar{D} meson cloud model we calculate the squared charm radius of the nucleon. The ratio between this squared radius and the ordinary baryon squared radius is identified with the probability of "seeing" the intrinsic charm component of the nucleon. Our estimate is compatible with those used to successfully describe the charm production phenomenology.

In the early eighties there was a hope to understand charm production solely in terms of perturbative QCD. In spite of all uncertainties in defining the scale, it would be in any case of the order of a few GeV and therefore the coupling constant would be smaller than one. As more and more data became available it became clear that perturbative QCD alone was not enough to properly account for the measured differential cross sections. Higher order corrections did not make the situation any better. The main problem was that the produced charmed particles were too fast. In other words, there was a remarkable excess of particles with large Feynman x (x_F).

Already at that time, the idea was advanced [1], that the hadron wave function contains a charm component even before undergoing a collision. This component is originated in higher twist QCD interactions inside the hadron. The so called "intrinsic" charmed pairs produced by these interactions have nothing to do with usual sea quark pairs. The crucial difference between them is that the intrinsic charm is part of the valence system and therefore very fast in contrast to the sea charm, which is slow. During the last years, an intrinsic charm component was added to the perturbative QCD component in a quantitative and systematic way [2]. As a result, a very good description of data was achieved. In order to obtain such good agreement with experimental data the crucial point was the normalization of the intrinsic charm component, σ_{ic} of the hadron + nucleon $\rightarrow c - \bar{c} X$ cross section. The quantity σ_{ic} is related to the probability of observing the intrinsic charm component of the hadron, P_{ic} [3]. It is very difficult (if not impossible) to calculate this quantity from first principles. It was estimated from a phenomenological analysis to be less than 1% [4]. In fact, $P_{ic} = 0.3\%$ seems to be the best value to describe recent data on charm production [2].

A very important question is, of course, whether this 1% of intrinsic charm can be supported by any model based calculation. In ref. [5], such a calculation was done using the MIT bag model. It was found that the probability of finding a five-quark component

$(uudc\bar{c})$ configuration bound within the nucleon bag is of 1 or 2%, in good agreement with the above mentioned phenomenological estimate.

In this note we calculate P_{ic} using an approach, which is completely different and independent from that used in ref. [1-5] and can therefore be used as a cross-check to those estimates.

The existence of intrinsic charm is here associated with low momentum components of a virtual $c\bar{c}$ pair in the nucleon. At low momentum scales, the virtual pair lives a sufficiently long time to permit the formation of charm hadronic components of the nucleon wave function. The same argument is true for the strange matrix elements.

Generally speaking, we can say that the proton is a fluctuating object, being sometimes a neutron plus a pion, sometimes a strange hyperon plus kaon and so on. It can be any combination of virtual hadrons possessing the right quantum numbers. In particular, if charmed pairs pre-exist inside the nucleon, it can oscilate into a charmed hyperon plus a D meson; as e.g., by the process

$$p \rightarrow \Lambda_c + \bar{D} \rightarrow p. \quad (1)$$

We calculate the intrinsic charm contribution to the matrix element $\langle N | \bar{c}\gamma_\mu c | N \rangle$ arising from this virtual \bar{D} meson cloud. The idea that intrinsic quark contributions to nucleon matrix elements can be given by meson clouds is not new. It was used in refs.[6, 7, 8, 9] to estimate the intrinsic strangeness content of the nucleon and it was suggested in ref [1] as a picture to understand the existence of intrinsic charm in the nucleon.

As in ref.[6], we compute the \bar{D} meson loops using an effective meson-nucleon vertex characterized by a monopole form factor

$$F(k^2) = \frac{m^2 - \Lambda^2}{k^2 - \Lambda^2}, \quad (2)$$

and we introduce "seagull" terms in order to satisfy the Ward-Takahashi (WT) identity. In eq. (2) m is the meson mass and Λ is the effective cut-off. The inclusion of the meson-nucleon

form-factors is important to properly take into account the underlying nucleon structure and its spatial extension. As shown in ref.[8], when the sub-structure of the nucleon is considered, it is the size of the proton, rather than the masses involved in the loop, that determines the effective momentum cut-off. We expect therefore the effective cut-off in the \bar{D} meson-nucleon form factor to be approximately the same used in the pion-nucleon or kaon-nucleon form factors.

The pseudoscalar meson-baryon coupling for extended hadrons is schematically given by

$$\mathcal{L}_{BBM} = -ig_{BBM} \bar{\Psi} \gamma_5 \Psi F(-\partial^2) \phi, \quad (3)$$

where Ψ and ϕ are baryon and meson fields respectively, $F(k^2)$ is the form factor at the meson-baryon vertices and k is the momentum of the meson. The fact that the nucleon- \bar{D} - Λ_c coupling constant is not known is not important here because we are mostly interested in arriving at some upper limit to the intrinsic charm content of the nucleon and not at definitive numerical predictions. Accordingly we will use the pion-nucleon coupling constant as an upper limit to the nucleon- \bar{D} - Λ_c coupling constant.

We employ pointlike couplings between the current and the intermediate meson and baryon. For the vector current one has

$$\langle \Lambda_c(p') | \bar{c}\gamma_\mu c | \Lambda_c(p) \rangle = \bar{U}(p') \gamma_\mu U(p) \quad (4)$$

and

$$\langle \bar{D}(p') | \bar{c}\gamma_\mu c | \bar{D}(p) \rangle = -(p + p')_\mu \quad (5)$$

in a convention where the c -quark has charm charge=+1.

The effective lagrangian eq.(3) is non-local and this induces an electromagnetic vertex current if the photon is present. In order to maintain gauge invariance we have to take into account the "seagull vertex"

$$i\Gamma_\mu(k, q) = \pm g_{N\Lambda_c \bar{D}} \gamma_5 (q \pm 2k)_\mu \frac{F(k^2) - F((q \pm k)^2)}{(q \pm k)^2 - k^2}, \quad (6)$$

which is generated via minimal substitution [10]. The upper and lower signs in eq.(6) correspond to an incoming or outgoing meson respectively.

The three distinct contributions to the intrinsic form factors, associated with processes in which the current couples to the baryon line (B) (figure 1a), to the meson line (M) (figure 1b) or to the meson-baryon vertex (V) (figure 1c and 1d) in the loop are given by

$$\Gamma_\mu^B(p', p) = -ig_{N\Lambda_c\bar{D}}^2 \int \frac{d^4k}{(2\pi)^4} \Delta(k^2) F(k^2) \gamma_5 S(p', k) \gamma_\mu S(p, k) \gamma_5 F(k^2), \quad (7)$$

$$\Gamma_\mu^M(p', p) = ig_{N\Lambda_c\bar{D}}^2 \int \frac{d^4k}{(2\pi)^4} \Delta((k+q)^2) (2k+q)_\mu \Delta(k^2) F((k+q)^2) \gamma_5 S(p, k) \gamma_5 F(k^2), \quad (8)$$

$$\Gamma_\mu^V(p', p) = ig_{N\Lambda_c\bar{D}}^2 \int \frac{d^4k}{(2\pi)^4} F(k^2) \Delta(k^2) \left[\frac{(q+2k)_\mu}{(q+k)^2 - k^2} (F(k^2) - F((k+q)^2)) \times \right. \\ \left. \gamma_5 S(p-k) \gamma_5 - \frac{(q-2k)_\mu}{(q-k)^2 - k^2} (F(k^2) - F((k-q)^2)) \gamma_5 S(p'-k) \gamma_5 \right]. \quad (9)$$

In the above equations

$$\Delta(k^2) = \frac{1}{k^2 - m^2 + i\epsilon} \quad (10)$$

is the meson propagator and

$$S(p, k) = \frac{1}{\not{p} - \not{k} - M_\Lambda + i\epsilon} \quad (11)$$

is the Λ_c propagator and $p' = p + q$ with q being the photon momentum. In figure 1 we show all momentum definitions.

With these amplitudes it is easy to show that the Ward-Takahashi identity

$$q^\mu (\Gamma_\mu^B(p', p) + \Gamma_\mu^M(p', p) + \Gamma_\mu^V(p', p)) = Q_c (\Sigma(p) - \Sigma(p')), \quad (12)$$

is satisfied. In eq.(12) Q_c is the nucleon charm charge, $Q_c = 0$, and $\Sigma(p)$ is the self-energy of the nucleon related to the \bar{D} Λ_c loop. The sum of the three amplitudes also ensures the charge non-renormalization (or the Ward Identity)

$$(\Gamma_\mu^B + \Gamma_\mu^M + \Gamma_\mu^V)_{q=0} = Q_c \left(-\frac{\partial}{\partial p^\mu} \Sigma(p) \right) = 0. \quad (13)$$

The intrinsic charm form factors are obtained by writing these amplitudes in terms of the Dirac and Pauli form factors

$$\Gamma_\mu(p', p) = \gamma_\mu F_1^c(q^2) + i \frac{\sigma_{\mu\nu} q^\nu}{2M_N} F_2^c(q^2). \quad (14)$$

The intrinsic squared charm radius of the nucleon is defined as

$$r_c^2 = 6 \left. \frac{\partial G_E^c(q^2)}{\partial q^2} \right|_{q^2=0}, \quad (15)$$

where $G_E^c(q^2)$ is the electric form factor introduced by Sachs [11]

$$G_E^c(q^2) = F_1^c(q^2) + \frac{q^2}{4M_N^2} F_2^c(q^2). \quad (16)$$

The numerical results for $|r_c^2|$ are shown in figure 2, as a function of the form factor cut-off Λ . The value of the coupling and masses used are $M_N = 939$ MeV, $M_{\Lambda_c} = 2285$ MeV, $m_{\bar{D}} = 1865$ MeV and $g_{N\Lambda_c\bar{D}}/\sqrt{4\pi} = g_{N\pi N}/\sqrt{4\pi} = -3.795$

The intensity of a given proton fluctuation is associated with its average squared radius $|r^2|$. The larger is $|r^2|$, the more frequently we will find the proton in that particular oscillation and the larger will be the probability of "seeing" it.

We shall assume that the average barionic radius of the proton ($r_p = [\langle r_B^2 \rangle]^{1/2} \sim 0.72 fm$) associated with the isoscalar part of the electromagnetic current is a good measure of the proton "total size", i.e., the size which takes into account all possible fluctuations that couple to isoscalar currents. The intrinsic charm probability is then given by

$$P_{ic} = \frac{|r_c^2|}{r_p^2} = 0.9\% \quad (13)$$

where $|r_c^2| = 0.0047 fm^2$ is the average charm squared radius calculated above with a cut-off $\Lambda = 1.2$ GeV. P_{ic} is the ratio between the charm "area" and the total proton "area".

We want to compare our results with those obtained by Donoghue and Golowich in ref. [5] for the five quark components of the proton wave function, $|uuds\bar{s}\rangle$ and $|uudq\bar{q}\rangle$, where

q represents a light quark. We repeat then the calculations for kaon and pion loops (with the same cut-off Λ), obtaining the average strange radius $|r_s^2| = 0.025 fm^2$ and the average light quark radius $|r_q^2| = 0.130 fm^2$. Dividing these radii by the barionic squared radius used above we obtain the probabilities $P_{is} = 5 \%$ and $P_{iq} = 25 \%$. The calculations done in ref. [5] arrive at $P_{is} = 16 \%$ and $P_{iq} = 31 \%$. The discrepancy in the strange sector suggests that the vector meson dominance model contribution coming from the $\omega - \phi$ mixing (see ref. [9]) is really important . In fact, it will change the result from $P_{is} = 5 \%$ to $P_{is} = 10 \%$ [9]. As there is no experimental evidence for a $\omega - J/\Psi$ mixing , the vector meson model will not contribute in the charm sector. With the inclusion of the $\omega - \phi$ mixing our results agree with those obtained in ref. [5] within 6 %.

The charm squared radius increases with Λ (as it can be seen in figure 2) reaching $|r_c^2| = 0.016 fm^2$ at asymptotically large values of Λ . In this limit we would have $P_{ic} = 3.0 \%$. Considering that we are overestimating the coupling constant in the charm loop, this number can be taken as an upper limit for the intrinsic charm probability in the context of our calculation scheme. Our result seems to corroborate the previous estimates [1-5] .

In this work we have only considered loops involving the particular combination $\bar{D}-\Lambda_c$. In principle we could include loops with $\bar{D}-\Sigma_c$ and also with vector mesons. However in the case of the intrinsic strangeness these contributions were shown [6] to be much less important than the $\bar{D}-\Lambda_c$ loops. The Σ_s couples very weakly to the nucleons and the vector mesons have large masses , their contribution being thus suppressed. In our case, due to the lack of knowledge of the relevant couplings and cut-offs , no attempt is made to go beyond the $\bar{D}-\Lambda_c$ loop. We expect this contribution to be the most significant, specially in view of the very large values of the coupling constant and cut-off used here. This might be sufficient for an estimate of the order of magnitude of P_{ic} .

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Figure Captions

Figure 1. Diagrams which contribute to the calculation of the vertex function. Solid external lines represent the proton and solid internal lines represent the Λ_c . Dashed and wavy lines represent the \bar{D} and the vector current respectively.

Figure 2. The intrinsic charm mean square radius of the nucleon as a function of the cut-off Λ in the baryon-meson form factor.

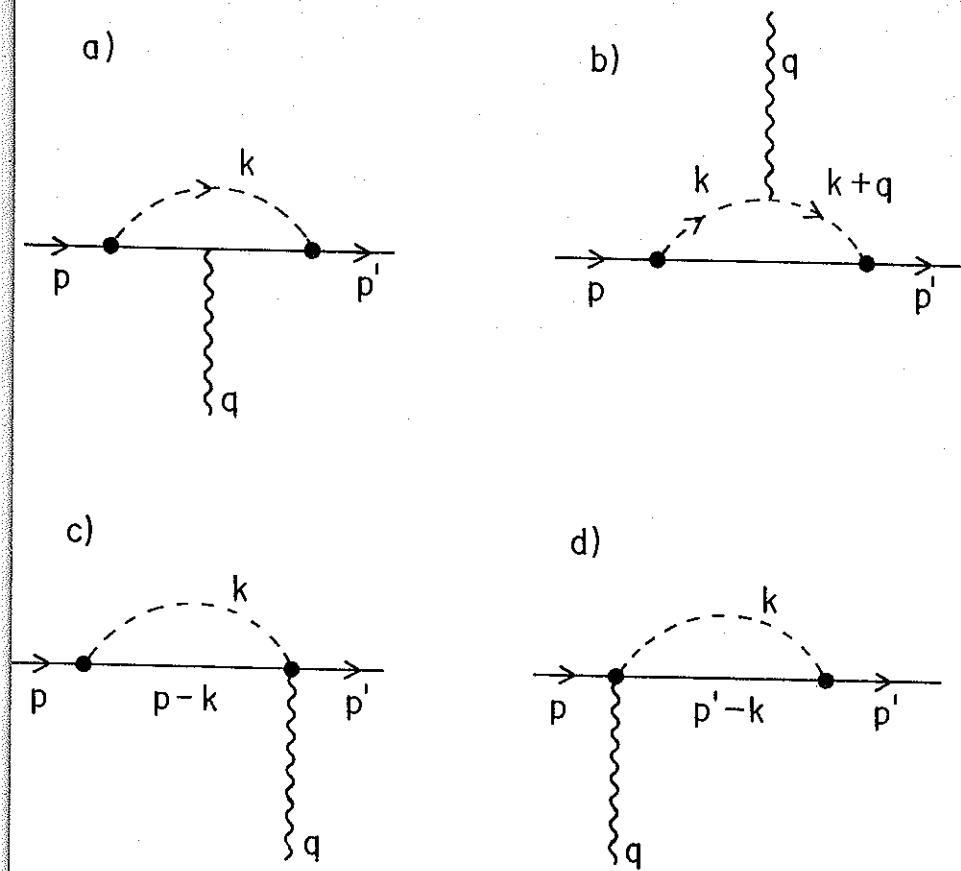


Figure 1

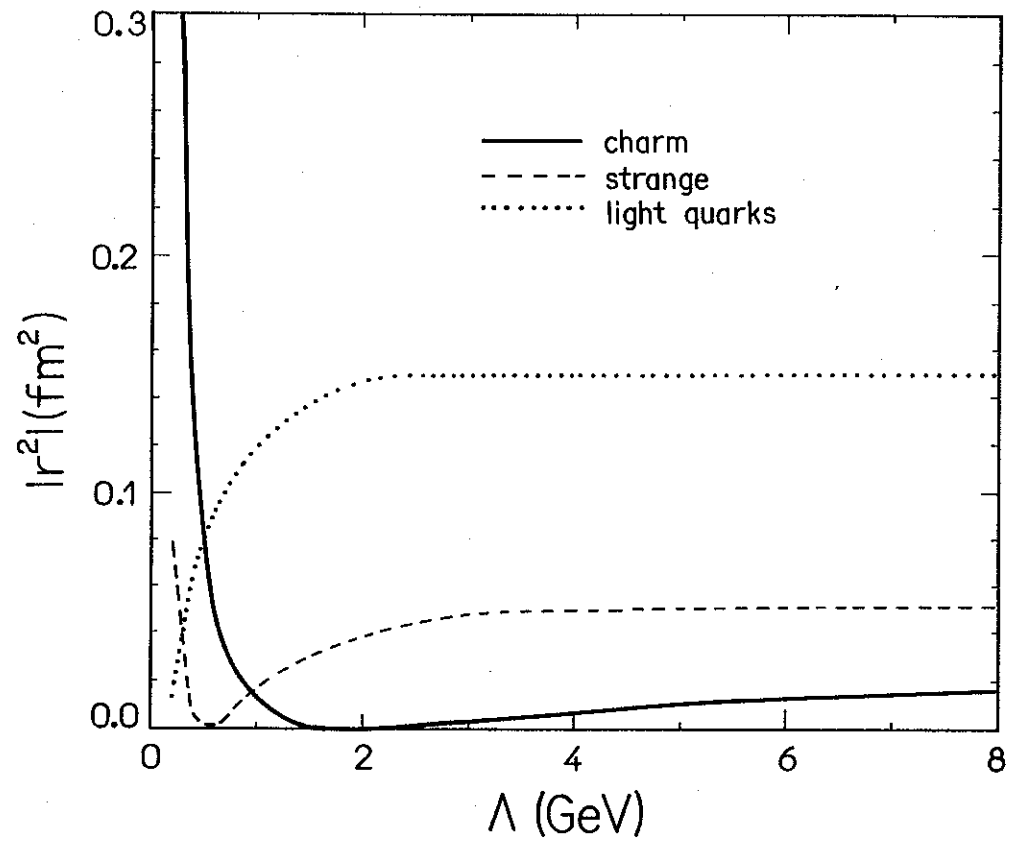


Figure 2