Intrinsic charm component of the nucleon

F. S. Navarra, M. Nielsen, C. A. A. Nunes, and M. Teixeira
Nuclear Theory and Elementary Particle Phenomenology Group, Instituto de Física da Universidade de São Paulo, Caixa Postal 66318, 05389-970 São Paulo, Brazil
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Using a $\overline{D}$ 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. However, because of the lack of relevant experimental information, a large uncertainty in our result is unavoidable. [S0556-2821(96)02811-1]

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In the early 1980s there was the hope that one could understand charm production solely in terms of perturbative QCD. In spite of all the 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 [1] improved the results but did not solve the problems. The main difficulty 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). In addition a ''leading particle'' effect has been observed [2]: i.e., charmed mesons carrying one of the valence quarks of the projectile are faster than those carrying no projectile valence quark. This is very hard to explain on the basis of parton fusion alone and is considered as evidence of some nonperturbative production mechanism.

Already over ten years ago, the idea was advanced [3] that the hadron wave function contains a charm component even before undergoing collision. This component is originated in higher-twist QCD interactions inside the hadron. The so-called ''intrinsic'' charmed pairs produced by these interactions are different from 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 with 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 [4]. 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 $\rightarrow c-\overline{c}X$ cross section. The quantity σ_{ic} is related to the probability of observing the intrinsic charm component of the hadron, P_{ic} [5]. It is very difficult to calculate this quantity from first principles. It was estimated from a phenomenological analysis to be less than 1% [6]. In fact, $P_{ic}=0.3\%$ seems to be the best value to describe recent data on charm production [4].

A very important question is, of course, whether this 1% of intrinsic charm can be supported by any model-based calculation. In Ref. [7], such a calculation was done using the MIT bag model. It was found that the probability of finding a five-quark component $|uudc\overline{c}\rangle$ configuration bound within the nucleon bag is 1 or 2%, in good agreement with the above-mentioned phenomenological estimate.

In this paper we calculate P_{ic} using an approach that is completely different and independent from that used in Refs. [3–7] 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-$\overline{c}$ 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. It is this component that, when the nucleon is boosted, will move as fast as the valence quarks.

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 preexist inside the nucleon, it can fluctuate into a charmed hyperon plus a $\overline{D}$ meson, as e.g., by the process

$$p\rightarrow\Lambda_c+\overline{D}\rightarrow p. \tag{1}$$

We calculate the intrinsic charm contribution to the matrix element $\langle N|\overline{c}\gamma_\mu c|N\rangle$ arising from this virtual $\overline{D}$ 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. [8–11] to estimate the intrinsic strangeness content of the nucleon and it was suggested in Ref. [3] as a picture to understand the existence of intrinsic charm in the nucleon.

As in Ref. [8], we compute the $\overline{D}$ meson loops using an effective meson-nucleon vertex characterized by a monopole form factor

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

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 cutoff. 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. [10], when the substructure of the nucleon is considered, it is the size of the proton, rather than the masses involved in the loop, which determines the effective momentum cutoff. We expect therefore the effective cutoff 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

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

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 primarily 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

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

and

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

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

The effective Lagrangian Eq. (3) is nonlocal 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’’

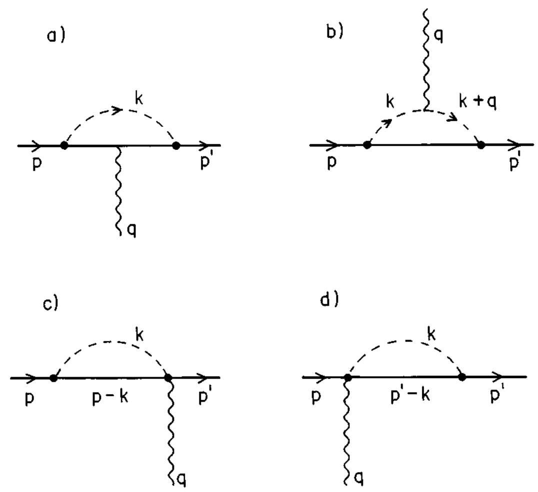

FIG. 1. Diagrams which contribute to the calculation of the vertex function. Solid external lines represent the proton and solid internal lines represent the Λ_c. Dashed and wavy lines represent the $\bar{D}$ and the vector current, respectively.

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

which is generated via minimal substitution [12]. 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) [Fig. 1(a)], to the meson line (M) [Fig. 1(b)] or to the meson-baryon vertex (V) [Figs. 1(c) and 1(d)] in the loop are given by

$$\Gamma^B_\mu(p',p)=-ig^2_{N\Lambda_c\bar{D}}\int\frac{d^4k}{(2\pi)^4}\Delta(k^2)F(k^2)\gamma_5S(p'-k)\gamma_\mu S(p-k)\gamma_5F(k^2), \tag{7}$$

$$\Gamma^M_\mu(p',p)=ig^2_{N\Lambda_c\bar{D}}\int\frac{d^4k}{(2\pi)^4}\Delta((k+q)^2)(2k+q)_\mu\Delta(k^2)F((k+q)^2)\gamma_5S(p-k)\gamma_5F(k^2), \tag{8}$$

$$\Gamma^V_\mu(p',p)=ig^2_{N\Lambda_c\bar{D}}\int\frac{d^4k}{(2\pi)^4}F(k^2)\Delta(k^2)\left[\frac{(q+2k)_\mu}{(q+k)^2-k^2}[F(k^2)-F((k+q)^2)]\right.$$
$$\left.\times\gamma_5S(p-k)\gamma_5-\frac{(q-2k)_\mu}{(q-k)^2-k^2}[F(k^2)-F((k-q)^2)]\gamma_5S(p'-k)\gamma_5\right]. \tag{9}$$

In the above equations

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

is the meson propagator and

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

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

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

$$q^\mu[\Gamma^B_\mu(p',p)+\Gamma^M_\mu(p',p)+\Gamma^V_\mu(p',p)]$$
$$=Q_c[\Sigma(p)-\Sigma(p')] \tag{12}$$

is satisfied. In Eq. (12) Q_c is the nucleon charm charge,

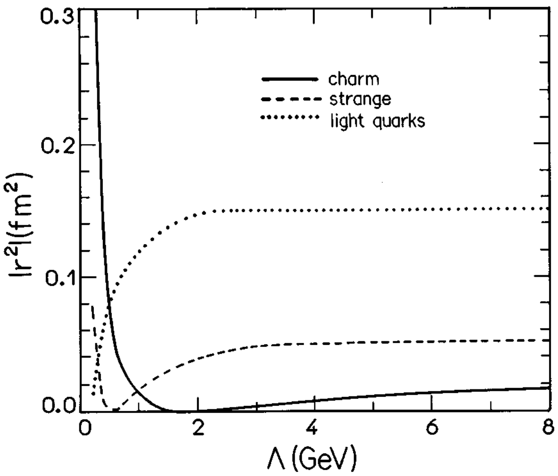

FIG. 2. The intrinsic charm mean square radius of the nucleon as a function of the cutoff Λ in the baryon-meson form factor.

$Q_c=0$, and $\Sigma(p)$ is the self-energy of the nucleon related to the D-Λ_c loop. The sum of the three amplitudes also ensures charge nonrenormalization (or the Ward Identity):

$$(\Gamma^B_\mu+\Gamma^M_\mu+\Gamma^V_\mu)_{q=0}=Q_c\left(-\frac{\partial}{\partial p^\mu}\Sigma(p)\right)=0. \tag{13}$$

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

$$\Gamma_\mu(p',p)=\gamma_\mu F^c_1(q^2)+i\frac{\sigma_{\mu\nu}q^\nu}{2M_N}F^c_2(q^2). \tag{14}$$

The intrinsic squared charm radius of the nucleon is defined as

$$r^2_c=6\frac{\partial G^c_E(q^2)}{\partial q^2}\bigg|_{q^2=0}, \tag{15}$$

where $G^c_E(q^2)$ is the electric form factor introduced by Sachs [13]:

$$G^c_E(q^2)=F^c_1(q^2)+\frac{q^2}{4M^2_N}F^c_2(q^2). \tag{16}$$

The numerical results for $|r^2_c|$ are shown in Fig. 2, as a function of the form factor cutoff 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 $g_{N\Lambda_c\bar{D}}/\sqrt{4\pi}=g_{N\pi N}/\sqrt{4\pi}=-3.795$.

As can be seen the results depend very strongly on the value of Λ. The region of very small values of Λ does not give realistic results for $|r^2_c|$ because it corresponds to a very large proton size. The region with values of Λ around the meson mass is also not reliable because it gives results that are just an artifact of the parametrization of the form factor. The asymptotic region of large Λ is interesting because it provides results which are weakly dependent on the cutoff.

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

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

$$P_{ic}=\frac{|r^2_c|}{r^2_p}=0.9\%, \tag{17}$$

where $|r^2_c|=0.0047$ fm^2 is the average charm squared radius calculated above with a cutoff $\Lambda=1.2$ 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. [7] 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 cutoff Λ), obtaining the average strange radius $|r^2_s|=0.025$ fm^2 and the average light quark radius $|r^2_q|=0.130$ fm^2. Dividing these radii by the baryonic squared radius used above we obtain the probabilities $P_{is}=5\%$ and $P_{iq}=25\%$. The calculations done in Ref. [7] 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 ω-ϕ mixing (see Ref. [11]) is really important. In fact, it will change the result from $P_{is}=5\%$ to $P_{is}=10\%$ [11]. As there is no experimental evidence for a ω-J/ψ mixing, the vector meson model will not contribute in the charm sector. With the inclusion of the ω-ϕ mixing our results agree with those obtained in Ref. [7] within 6%.

The charm squared radius increases with Λ (as can be seen in Fig. 2) reaching $|r^2_c|=0.016$ 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 be consistent with previous estimates [3–7].

As a further point we would like to compare our predictions for the x_F distributions of Λ_c and D in the meson cloud model with distributions obtained by Brodsky and collaborators. Following Ref. [3] we make a Fock-state decomposition of the proton. The difference is now that instead of, for example, five quarks $(uudc\bar{c})$ our state will contain a baryon plus a meson ($\bar{D}$-Λ_c). The probability distribution corresponding to this two-particle Fock state is, as in [3] and [5], assumed to have the form

$$P(x_{\Lambda_c},x_D)=\frac{N\delta(1-x_{\Lambda_c}-x_D)}{\left(m^2_p-\dfrac{\hat{m}^2_{\Lambda_c}}{x_{\Lambda_c}}-\dfrac{\hat{m}^2_D}{x_D}\right)^2}, \tag{18}$$

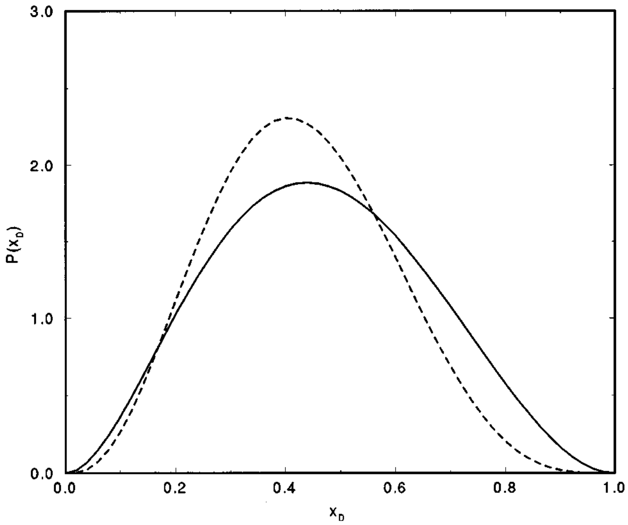

FIG. 3. Feynman x distribution of $\overline{D}$ mesons in the meson cloud model (solid line) and in the intrinsic charm model (dashed line).

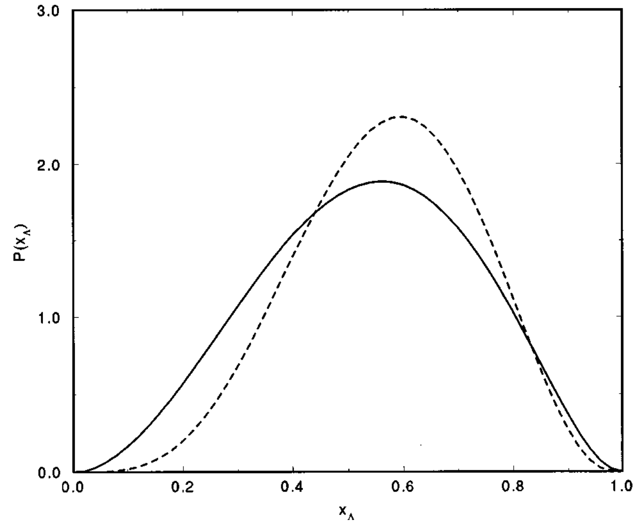

FIG. 4. Feynman x distribution of the charmed baryon Λ in the meson cloud model (solid line) and in the intrinsic charm model (dashed line).

where $\hat{m}_i^2 = m_i^2 + \langle k_T \rangle_i^2$ are the effective transverse masses, with $\langle k_T \rangle$ being the average transverse momentum. Since $m_{\Lambda_c}^2, m_D^2 \gg m_p^2, \langle k_T \rangle^2$ we can write

$$P(x_{\Lambda_c}, x_D) = \frac{N' x_{\Lambda_c}^2 x_D^2 \delta(1 - x_{\Lambda_c} - x_D)}{\left(x_{\Lambda_c} + \left(\frac{m_{\Lambda_c}}{m_D} \right)^2 x_D \right)^2}, \quad (19)$$

where $N' = 50.68$ is determined by imposing a normalization condition on $P(x_{\Lambda_c}, x_D)$. Integrating the equation above in x_D (x_{Λ_c}) we find the Λ_c $(\overline{D})$ x_F distribution, which is shown in Figs. 3 and 4 (solid lines). For the sake of comparison we also show in these figures the corresponding distributions obtained in Ref. [3] for Λ_c and $\overline{D}$ (dashed lines), by combining respectively the u, d, and c, and the u and $\overline{c}$ quarks in the $|uudc\overline{c}\rangle$ Fock state. It is interesting to notice that the x_F distributions look very similar in the two approaches. The results obtained here have a mass scale whereas there is no information about the Λ_c and $\overline{D}$ masses in the calculations of Ref. [3]. The existence of mass scales is responsible for the slight differences between the x_F distributions. From the phenomenological point of view the differences will not be noticeable. The resemblance between these curves is a strong indication that the idea of intrinsic charm can be well understood in terms of the meson cloud model.

Another straightforward extension of our calculations is the estimate of the botton content of the proton. Assuming $g_{N\Lambda_b B} = g_{N\Lambda_c D} = g_{\pi NN}$, the only differences will be the masses of the baryon and meson. In the asymptotic limit we get $P_{ib}/P_{ic} \sim 1/3$, which is different from the scaling proposed in Ref. [3]: $P_{ib}/P_{ic} \sim (m_c/m_b)^2 \sim 1/9$. However, this should not be taken as a discrepancy between the two approaches, since a very strong approximation of the value of the coupling constants was done by us to get the value $P_{ib}/P_{ic} \sim 1/3$.

In this work we have only considered loops involving the particular combination $\overline{D}$-Λ_c. In principle we could include loops with $\overline{D}$-Σ_c and also with vector mesons. However, due to the lack of knowledge of the relevant couplings and cutoffs, no attempt is made to go beyond the $\overline{D}$-Λ_c loop. We expect this contribution to be the most significant, especially in view of the very large values of the coupling constant and cutoff used here. This might be sufficient for an estimate of the order of magnitude of P_{ic}.

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