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5.4 Pion Cloud and Spin Structure of the Nucleon

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Inclusive deep-inelastic lepton-nucleon scattering with polarized beam and target is a useful tool for studying the spin structure of the nucleon. The lepton-nucleon asymmetry measured in such an experiment is conventionally defined by

$$A = d\sigma(\uparrow\downarrow-\uparrow\uparrow)/d\sigma(\uparrow\downarrow+\uparrow\uparrow), \quad (1)$$

where $\uparrow\downarrow$ and $\uparrow\uparrow$ indicate respectively antiparallel and parallel beam and target spin polarizations. Determination of the asymmetry in the scaling region provides a useful constraint on theoretical models of the nucleon spin structure.

The asymmetry A has recently been measured in inclusive deep-inelastic electron-proton scattering[1]. Although the data is consistent with several theoretical quark-parton model predictions[2-4], details of the spin structure of the nucleon remain obscure. This is due to our ignorance of the dynamical mechanisms which determine the quark spin distribution in a nucleon. In theoretical calculations of the asymmetry A, effects of the quark-antiquark($q\bar{q}$) sea are usually neglected. This is clearly not satisfactory since the $q\bar{q}$ sea in a polarized nucleon might be polarized[5]. Even if the $q\bar{q}$ sea is not polarized, it can have orbital angular momentum relative to the valence quark, thus changing the valence quark spin distribution. Using SU(3) symmetry, and Bjorken sum rules for the nucleon and Ξ, Sehgal[6] was able to estimate that about 40% of the angular momentum of a polarized proton arises from the orbital motion of its constituents. In this note, we show that a significant portion of this orbital angular momentum can be accounted for by the pion cloud surrounding the proton.

Consider the excitation of a p-wave pion in a physical proton. The pion has zero spin, so that its $q\bar{q}$ content is not polarized. However, there is one unit of angular momentum between the nucleon core and the meson, which contributes to the total angular momentum of the proton. Let us expand a polarized physical proton state in states with definite number of pions:

$$|p_\uparrow\rangle_{phy} = \alpha|p_\uparrow\rangle + \beta_{00}|\pi^0 p_\uparrow\rangle + \beta_{0-}|\pi^0 p_\downarrow\rangle + \beta_{-0}|\pi^+ n_\uparrow\rangle + \beta_{--}|\pi^+ n_\downarrow\rangle, \quad (2)$$

where we have included only zero- and one-pion states, which has been shown to be adequate in the cloudy bag model[7]. The expansion coefficients in Eq.(2) are related by the normalization condition

$$\alpha^2 + \sum\beta_i{}^2 = 1, \quad (3)$$

and

$$\sum\beta_i{}^2 = P_\pi, \quad (4)$$

gives the probability of finding a pion (π^0 or π^+) in a physical proton. Also, from the Clebsch-Gordon coefficients involved in the spin and isospin couplings in Eq.(2), we have

$$\beta_{00} : \beta_{0-} : \beta_{-0} : \beta_{--} = 1 : \sqrt{2} : \sqrt{2} : 2 \quad (5)$$

The pion probability P_π can be expressed in terms of familiar quantities[8-9]:

$$P_\pi = 3g^2/16\pi^2 \int_0^1 dx \int_{M^2x^2/(1-x)}^{\infty} dt\ tu^2(t)/(t+m_\pi^2)^2, \qquad (6)$$

where g=13.6 is the pion-nucleon coupling constant, and u(t) is the πNN vertex form factor. Using the cloudy bag model form factor corresponding to a nucleon bag radius of 0.9 fm (a radius of about this size is required to fit the static properties of the nucleon, and also π-N scattering data[10-11]), Eq.(6) gives $P_\pi = 0.18$, which implies that $\beta_{00}{}^2 = 0.02$. From these results, it is then straightforward to show that the orbital angular momentum associated with the pion cloud is given by

$$L_z(\pi) = \beta_{0-}{}^2 + \beta_{--}{}^2 = 0.12 \qquad (7)$$

Eq.(7) indicates that about 24% of the total angular momentum (1/2) of a proton can be attributed to the orbital motion of the pion cloud around the nucleon core, which is a significant portion of the 40% orbital angular momentum found by Sehgal[6]. A consequence of the virtual pion excitation is that the proton spin polarization is effectively diluted. That is, the quark spin polarization magnitude of a 100% polarized physical proton, as seen by a virtual photon in a deep-inelastic process, is less than unity. A discussion of this effect on the lepton-nucleon asymmetry A, defined in Eq.(1), can be found in Ref.(12).

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