

Pion exchange and the H1 forward spectrometer data

A.W. Thomas, C. Boros

Department of Physics and Mathematical Physics and Special Research Centre for the Subatomic Structure of Matter,
University of Adelaide, SA 5005, Australia

Received: 4 December 1998 / Revised version: 1 February 1999 / Published online: 27 April 1999

Abstract. We point out that the $\Delta\pi$ component of the nucleon wave function is vital to the interpretation of the recent H1 data for leading baryon production. While the n/p ratio is equal to two with the $N\pi$ component alone, the inclusion of the $\Delta\pi$ component brings this ratio very near to unity, as observed in the experiment. This result demonstrates that pion exchange can not only account for leading neutron but also for a large fraction of the leading proton production.

1 Introduction

Over the past few years data collected at DESY have vastly increased our store of knowledge concerning nucleon structure functions. One particular class of events, discovered by the ZEUS [1] and the H1 [2] collaborations, has caused enormous interest. These are the “rapidity gap events”, which amount to some 10% of the total deep inelastic cross section. Events in this class are characterised by a large, particle free gap in rapidity between the region of phase space occupied by the debris of the target proton and the jet associated with the interaction current.

While these events certainly involve the Pomeron and have provided important new information concerning its properties, it has also been realised for some time that the pion cloud of the nucleon, required by non-perturbative QCD because of dynamical symmetry breaking, may play a role [3]. Although the rapidity gaps are much smaller in pion exchange than in Pomeron exchange [4], both are characterised by the production of fast baryons in the forward region. The pion cloud was first discussed in the context of deep inelastic scattering by Feynman [5] and Sullivan [6]. It was later realised that, as well as leading to an excess of non-strange over strange sea quarks, the pion cloud would yield a significant excess of \bar{d} over \bar{u} quarks in the proton [7].

This mechanism for violating the Gottfried sum rule, while preserving isospin, has been extensively studied theoretically [8] since the New Muon Collaboration discovered that the Gottfried sum rule was violated [9] – for recent reviews see [10–12]. Later experiments by NA51 (at CERN) [13], E866 (at Fermilab) [14] and most recently HERMES (at DESY) [15] have given us quite detailed information on the shape of $\bar{d}(x)/\bar{u}(x)$ and it is clear that the pion cloud plays an important role in understanding this data [16]. From the phenomenological point of view,

once one can establish the role of pions in this type of diffractive event one can use such data to study the pion structure function at small x [17] – something that is difficult to obtain any other way [18].

In order to specifically study the role of pions in the rapidity gap events, the H1 detector was upgraded by the addition of a forward proton spectrometer (FPS) and a forward neutron spectrometer (FNS). Both were specifically designed to detect forward going hadrons with p_T up to 200 MeV/c (recall that the beam momentum is 800 GeV/c!). The expectation of the collaboration was that if pion exchange alone were responsible for leading baryon production, the ratio of n to p production would be in the ratio 2:1 – coming from the square of the isospin Clebsch-Gordon coefficients for $p \rightarrow n\pi^+$ and $p \rightarrow p\pi^0$ ($\frac{2}{3}$ and $\frac{1}{3}$, respectively).

The results of the H1 measurements were released recently [19]. A major finding was that in the relevant region of phase space the semi-inclusive proton production cross section was slightly larger than that for neutrons and that this ruled out pion exchange as the main mechanism for leading protons. Our purpose is to point out that, while the proton data does require other mechanisms as well, a large fraction of the proton events can indeed be understood in terms of pion exchange. We stress that the expectation of a 2:1 ratio is a little too naive and that well established physics associated with the pion cloud of the nucleon leads us to expect the experimental ratio to be closer to 1:1. While the role of the Δ in these processes was discussed quantitatively by Szczurek et al. [17] the experimental analysis totally omits any consideration of it. Our aim here has therefore been to specifically avoid the details of the experimental acceptance, but concentrate on the essential physics of this experiment. In this way we hope to focus attention on the need to reanalyse the data taking the effects of the Δ resonance into account.

2 The pion cloud of the nucleon

A complete analysis of the H1 data requires a full Monte-Carlo calculation including momentum acceptance cuts that can only be done by the collaboration. Our purpose is to present some physics which has so far been omitted from the analysis, which is nevertheless vital to the interpretation of the data.

A full solution of QCD with dynamical symmetry breaking is still just a dream for theorists. For the present we rely on a mixture of QCD motivated models and phenomenology. Although there are now many sophisticated chiral quark models of nucleon structure, it is often not easy to appreciate the physics. The cloudy bag model (CBM) [20] is both physically transparent and produces a picture of the nucleon, especially the probabilities for specific meson-baryon Fock states, that is in remarkably close agreement with modern analyses of the meson contribution to the spin and flavor structure of the nucleon – see [10]. While we use it to guide our discussion, we expect the general features to be quite robust.

Under SU(6) symmetry the N and Δ are degenerate and hence we might expect to treat them on the same footing. In the CBM, even though the $N - \Delta$ degeneracy is removed, this is still true. The transitions $N \rightarrow N\pi$ and $N \rightarrow \Delta\pi$ do not change the orbital occupied by the active valence quark. As a result the two processes have coupling constants that are large and similar in magnitude. Under SU(6) symmetry the momentum dependence of the two vertex functions is identical – in the CBM it is $3j_1(kR)/kR$ which, for many practical purposes may be approximated by $e^{-0.1k^2R^2}$, with R the bag radius. This seems phenomenologically reasonable because the axial form factor of the nucleon and for the $N \rightarrow \Delta$ transition are very similar in shape [21]. The relatively large excitation energies and smaller coupling constants for transitions to higher mass baryons suppress their contribution to nucleon properties, so that in practice the major effects come from $N\pi$ and $\Delta\pi$ components of the wave function.

The dominant Fock components of the p , with their probabilities, are therefore:

$$\begin{aligned} \pi^+ n &: \frac{2}{3}P_{N\pi} & ; & \quad \pi^0 p : \frac{1}{3}P_{N\pi} \\ \pi^- \Delta^{++} (\rightarrow \pi^+ p) &: \frac{1}{2}P_{\Delta\pi} \\ \pi^0 \Delta^+ (\rightarrow \pi^+ n / \pi^0 p) &: \frac{1/2}{3/3} & : & \quad \frac{1}{3}P_{\Delta\pi} \\ \pi^+ \Delta^0 (\rightarrow \pi^0 n / \pi^- p) &: \frac{2/1}{3/3} & : & \quad \frac{1}{6}P_{\Delta\pi}. \end{aligned} \quad (1)$$

Based on experience with the CBM as well as the phenomenological analysis of deep inelastic scattering data in the meson cloud model [10,16], we expect the total probability of the $N\pi$ Fock component ($P_{N\pi}$) to be 18-20%, while the $\Delta\pi$ probability ($P_{\Delta\pi}$) would be 6-12%.

We recall that the FPS and FNS limit p_T to less than 200 MeV/c. Since the vertex functions for $N \rightarrow N\pi$ and $N \rightarrow \Delta\pi$ are approximately the same, as explained earlier, the distribution of N 's and Δ 's in p_T will be essentially

Table 1. Neutron to proton ratios under the scenarios described in the text – the $N\pi$ probability is chosen to be 18%

Case	$P_{\Delta\pi} = 6\%$	$P_{\Delta\pi} = 9\%$	$P_{\Delta\pi} = 12\%$
(a)	1.25	1.08	0.96
(b)	1.12	0.93	0.80

identical. Of course, the Δ will decay well before reaching the forward spectrometers. Most of the time this will produce a proton, and as the typical transverse momentum in the decay of the Δ is also around 200 MeV/c these will mostly be detected by the FPS. Even in the case where a n is produced by the decay of the Δ , the pion will pass through the forward spectrometer and be vetoed by the FNS, thus counting as a “proton”.

The exact detection efficiencies are a matter for the experimental group's Monte Carlo simulation. In order to estimate the effect of the $\Delta\pi$ Fock component we make two assumptions: a) only the protons produced by Δ decay will count as protons and anything else as a neutron; b) any charged particle produced by delta decay will look like a proton (since the FPS has no particle identification) and will be counted as such. Under assumption (a) and using the coefficients given in (1), the n over p ratio is:

$$R\left(\frac{n}{p}\right) = \frac{\frac{2}{3}P_{N\pi} + \frac{2}{9}P_{\Delta\pi}}{\frac{1}{3}P_{N\pi} + \frac{7}{9}P_{\Delta\pi}}. \quad (2)$$

On the other hand, under assumption (b) we find:

$$R\left(\frac{n}{p}\right) = \frac{\frac{2}{3}P_{N\pi} + \frac{1}{9}P_{\Delta\pi}}{\frac{1}{3}P_{N\pi} + \frac{8}{9}P_{\Delta\pi}}. \quad (3)$$

In Table 1 we show the n/p ratios for cases (a) and (b) for several choices of the $\Delta\pi$ probability, ranging from 6 to 12%. The larger values are favoured by many analyses, but in fact the ratio is not strongly dependent on it. It is always around unity and slightly below unity at the preferred, upper end of the range. (We do not show the dependence on $P_{N\pi}$, because the ratio is even less sensitive to that choice within the allowed range.) It should be noted here also that these numbers serve as a first estimate. The decay of Δ 's into nucleons will shift the energy distribution of these secondary particles to lower energy values decreasing these ratios somewhat at high energies. This effect is discussed in [17] and should be taken into account in the Monte Carlo simulations.

It should be clear from this analysis that the $\Delta\pi$ component of the wave function of the nucleon is vital to the interpretation of the H1 data, bringing the n/p ratio very near to unity, as observed in the experiment, rather than two.

3 Discussion

We have seen that the $\Delta\pi$ component of the nucleon wave-function is vital to the analysis of the FPS and FNS data

taken by the H1 collaboration. As we have emphasised this is not a unique example of its importance. In analysing the violation of the Gottfried sum rule, and more particularly the ratio of \bar{d}/\bar{u} , the $\Delta\pi$ and $N\pi$ components tend to cancel each other and the detailed description of the data requires a careful treatment of both components [16]. Within the CBM, the explicit presence of the Δ was essential to the rapid convergence properties of the theory – for example, the fact that the bare and renormalized $NN\pi$ coupling constants were typically within 10% of each other [20]. The left-right asymmetry data for inclusively produced pions, measured by the FNAL E704-Collaboration [22] using transversally polarized proton beams and unpolarized targets, also suggest the importance of the $\Delta\pi$ component in the nucleon wave function. The experimental observation that the asymmetry of π^+ and that of π^- have different signs can be understood if one notes that the spin of the baryon in the meson-baryon fluctuation determines the angular momentum dependence of the wave function and that the lowest lying components relevant for the production of the leading π^+ and π^- are the $N\pi$ and the $\Delta\pi$ components, respectively [23]. We could cite many other examples but for the present we simply urge the collaboration to include the $\Delta\pi$ component of the nucleon wavefunction in a full Monte Carlo analysis of the data.

Acknowledgement. This work was supported in part by the Australian Research Council.

References

1. M. Derrick et al. (ZEUS Collaboration), Phys. Lett. B **315**, 481 (1993)
2. T. Ahmed et al. (H1 Collaboration), Nucl. Phys. B **429**, 477 (1994)
3. C. Boros, Liang Zuo-tang, Phys. Rev. D **51**, R4615 (1995)
4. M. Przybycien, A. Szczurek, G. Ingelman, Z. Phys. C **74** (1997) 509
5. R. P. Feynman, Photon-Hadron Interactions (W. A. Benjamin, New York 1972)
6. J. D. Sullivan, Phys. Rev. D **5**, (1972) 1732
7. A. W. Thomas, Phys. Lett. B **126**, (1983) 97
8. E. M. Henley, G. A. Miller, Phys. Lett. B **251**, (1990) 453; A. I. Signal, A. W. Schreiber, A. W. Thomas, Mod. Phys. Lett. A **6**, (1991) 271; S. Kumano, Phys. Rev. D **43**, (1991) 3067; S. Kumano, J. T. Londergan, Phys. Rev. D **44**, (1991) 717
9. P. Amandruz et al. , Phys. Rev. Lett. **66**, (1991) 2712; Phys. Lett. B **292**, (1992) 159
10. J. Speth, A. W. Thomas, Adv. Nucl. Phys. **24**, (1998) 83
11. J. T. Londergan, A. W. Thomas, Prog. Part. Nucl. Phys. **41**, (1998) 49
12. S. Kumano, Phys. Rep. **303**, (1998) 103
13. A. Baldit et al., Phys. Lett. B **332**, (1994) 244
14. E. A. Hawker et al., Phys. Rev. Lett. **80**, (1998) 3715
15. K. Ackerstaff et al. (Hermes Collaboration), Phys. Rev. Lett. **58** (1998) 5519
16. W. Melnitchouk, J. Speth, A. W. Thomas, Phys. Rev. D **59** (1999) 014033
17. A. Szczurek, N. N. Nikolaev, J. Speth, Phys. Lett. B **428**, (1998) 383; K. Golec-Biernat, J. Kwiecinski, A. Szczurek, Phys. Rev. D **56**, (1997) 3955; H. Holtmann et al., Phys. Lett. B **338**, (1995) 363
18. J. T. Londergan, G. Q. Liu, A. W. Thomas, Phys. Lett. B **361**, (1995) 110
19. C. Adloff et al. (H1 Collaboration), Eur. Phys. J. C **6**, (1999) 587
20. S. Théberge, G. A. Miller, A. W. Thomas, Phys. Rev. D **22**, (1980) 2838; D **23**, (1981) 2106(E); A. W. Thomas, Adv. Nucl. Phys. **13**, (1984) 1; G. A. Miller, Quarks and Nuclei **1**, (1984) 189
21. G. T. Jones et al., Z. Phys. C **43**, (1989) 527; T. Kitagaki et al., Phys. Rev. D **42**, (1990) 1331
22. D. L. Adams et al. (FNAL 704 Collaboration), Phys. Lett. B **261** (1991) 201; Phys. Lett. B **264** (1991) 461; B **276** (1992) 531; Z. Phys. C **56** (1992) 181; A. Bravar et al., Phys. Rev. Lett. **75** (1995) 3073 and **77** (1996) 2626
23. C. Boros, Phys. Rev. D **59** (1999) 051501