Explanation of the Apparent Charge Dependence of the Pion-Nucleon Coupling

Anthony W. Thomas and Karl Holinde[(a)]

Department of Physics and Mathematical Physics, The University of Adelaide, P.O. Box 498, Adelaide 5001, South Australia, Australia

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A recent, careful analysis of the world data on *pp* scattering concluded that the $pp\pi^0$ coupling constant was 3%–4% less than expected from charge independence and the known $pn\pi^+$ coupling constant. We propose a much simpler interpretation of the analysis of the *pp* data which involves no unreasonable level of charge dependence. Instead one must recognize that the pion-nucleon form factor needed in a boson-exchange model of the nucleon-nucleon force differs significantly from that relevant to a free nucleon.

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Bergervoet *et al.* recently reported[1,2] an exceptionally large violation of isospin in the pion-nucleon coupling constants. From a careful study of the $pp\pi^0$ vertex needed in *p-p* scattering they extracted a coupling constant (f_0) some 3% to 4% lower than that associated with the $pn\pi^+$ vertex (f_c). This announcement has met with widespread disbelief as no model has predicted effects bigger than a few tenths of a percent.[3–5] We propose that while their analysis of *p-p* scattering may well be correct (and an independent analysis would be most valuable), the interpretation as a violation of charge independence is probably not correct. Instead we suggest that their result is consistent with other evidence which suggests that the $NN\pi$ form factor of a free nucleon is much softer than that conventionally used in boson-exchange models of the *N-N* force.[6] Such a difference seems likely if one views the boson-exchange models as an effective description of some more complicated *N-N* interaction mechanism (e.g., involving quark and gluon exchange) when the nucleons overlap.

In what follows we shall briefly review the evidence concerning the $NN\pi$ form factor. However, to make it clear why this is necessary let us summarize our essential argument here. In particular, we wish to stress that the information on the charged- and neutral-pion coupling constants comes from different sources. Pion-nucleon dispersion relations determine the charged-pion–nucleon form factor $f_c(\mathbf{q}^2)$ at the nucleon pole ($\mathbf{q}^2=-m_\pi^2$). (The particular value at that point will be called simply f_c.) For simplicity our entire discussion will be referred to a parametrization of the momentum dependence of this vertex as a monopole,

$$f_c(\mathbf{q}^2)=f_c\frac{\Lambda^2-m_\pi^2}{\Lambda^2+\mathbf{q}^2}\,, \tag{1}$$

and we have anticipated that in *N-N* scattering $q^0\approx 0$, so that the four-momentum transfer squared which we need is usually minus the three-momentum transfer squared. As we shall discuss below, Λ for a free nucleon (called Λ_F) is of order 800 MeV or less. This leads to a charged-pion coupling constant at zero momentum transfer $[f_c(\mathbf{q}^2=0)]$ smaller than f_c by an amount of order m_π^2/Λ_F^2. On the other hand, small-angle *p-p* elastic scattering data involve three-momentum transfers which are slightly positive and near zero (see particularly the discussion in Sec. 8.2 of Ref. 6). Thus the $pp\pi^0$ coupling constant extracted by Bergervoet *et al.* is not f_0 but rather $f_0(\mathbf{q}^2=0)$. With Λ_F of order 800 MeV this is a correction of order 3%, which explains the apparent discrepancy. (We have also checked numerically that with such a small Λ_F the empirically required small tensor combination Δ_T of triplet-*p* phases is obtained.)

Before we discuss the free pion-nucleon form factor in more detail it is important to make some comments about *N-N* scattering. There can be no dispute about the fact that a boson-exchange description of the *N-N* force requires a πNN form factor with a much larger value of Λ (denoted Λ_{NN}). For example, the model-independent work of Ericson and Rosa-Clot[7,8] on the asymptotic *D/S* ratio in the deuteron showed that Λ_{NN} needed to be greater than 1 GeV, with a larger value preferred. The Bonn group found a lower limit on Λ_{NN} of 1.3 GeV with values as high as 1.5 or 1.75 GeV preferred in some fits.[6] A cutoff mass of order 800 MeV, as we mentioned above, would do irrepairable damage to the Bonn fit—especially to deuteron properties.

The conventionally large value of Λ_{NN} is what lies behind the claim of Bergervoet *et al.* that inclusion of a πNN form factor would not alter their conclusions. However, the point is that they determine $f_0(\mathbf{q}^2)$ at $\mathbf{q}^2\simeq 0$, and to test charge independence it must be compared with $f_c(\mathbf{q}^2)$ at $\mathbf{q}^2=0$. Since f_c is obtained from data on a single nucleon at $\mathbf{q}^2=-m_\pi^2$ the extrapolation to $f_c(\mathbf{q}^2=0)$ must be carried out using the πNN form factor appropriate to a free nucleon.

Next we turn to the case of the free pion-nucleon form factor. Unfortunately it is a quantity on which there is little direct experimental information. Within the particle physics community it has long been regarded as self-evident that it must be very closely related to the axial-vector form factor. For example, as long ago as 1976 Primakoff suggested using the same cutoff mass to estimate the induced pseudoscalar correction in muon capture.[9] In their estimate of leading-logarithmic corrections to nucleon self-energies, and hence the σ commutator, Gasser and Leutwyler hesitate to use a value of Λ (i.e., Λ_F) greater than 0.4 GeV and certainly not larger than 0.7 GeV.[10]

In many models of nucleon structure the axial-vector and the pion-nucleon form factors are closely related. For example, Guichon, Miller, and Thomas[11] considered a whole class of chiral bag models in which the pion was excluded from a sphere of arbitrary radius within a bag.[12] In all cases, ranging from the little bag[13] to the cloudy bag[14] the resulting πNN form factor was softer than the axial-vector form factor (i.e., $\Lambda_F < \Lambda_A$). This general result was confirmed within an improved constituent-quark model by Beyer and Singh.[15] The only model of which we are aware that gives a different result is that of Weise and collaborators.[16] Working in a Skyrme model supplemented with vector mesons they found the cutoff mass in the axial-vector form factor, Λ_A, to be about 750 MeV while Λ_F was about 850 MeV—that is, slightly larger. Nevertheless, even in this very different model the general result that $\Lambda_A \approx \Lambda_F$ still holds.

On the experimental side the axial-vector form factor is very well determined from charged-current neutrino scattering. It is usually fitted with a dipole form, and the world-average mass is 1.03 ± 0.04 GeV.[17] This would correspond to $\Lambda_A = 730$ MeV in a monopole. Neutral-current measurements have confirmed this value[18] (albeit in a region of slightly higher $\mathbf{q}^2$), and any upward deviation would lead to even worse problems[19,20] in interpreting the sum rule for the proton's spin structure function.

Schütte and Tillemans argued recently that Λ_F should be of order 600 MeV (or less) on the basis of a particular model of pion-nucleon scattering.[21] Within the cloudy bag model for the Δ resonance[14] too large a cutoff mass would lead to major problems—with the Chew-Low-Wick mechanism giving a resonance in addition to the quark-model pole.

Finally, the most direct evidence on the $NN\pi$ form factor actually comes from a surprising source. Some years ago we observed[22] that the pion cloud of the nucleon constitutes a sea of q-$\bar{q}$ pairs which breaks $SU(3)_F$ symmetry. This could be used to put a limit on the $NN\pi$ form factor. Very recently this analysis has been refined by Frankfurt, Mankiewicz, and Strikman,[23] who have extracted an even more stringent limit on Λ_F. Actually this process is sensitive to $\mathbf{q}^2$ and order $(2\text{–}3)m_\pi^2$ and hence the extracted mass was shape dependent—they found an upper limit of 500 MeV in a monopole and 900 MeV in a dipole.[23] The only significant ambiguity in this analysis is the possible off-mass-shell behavior of the pion structure function, but estimates suggest this would tend to lower Λ_F even more.[24]

In summary, every indication we have is that the cutoff mass in the pion-nucleon form factor *for a free nucleon* is close to that of the measured axial-vector form factor. We conclude that Λ_F is in the range 500–800 MeV, with 730 MeV the preferred value. As has been observed before,[11] such a value has important consequences for chiral symmetry and the Goldberger-Treiman relation. It is usually believed that the latter is good to about $(6 \pm 2)\%$, but correcting the pion-nucleon coupling to $\mathbf{q}^2 = 0$, rather than $\mathbf{q}^2 = -m_\pi^2$, with this range of values of Λ_F would give a correction of between 3% and 8%, which would essentially remove the discrepancy.

Let us return to the question of charged- and neutral-pion coupling constants. Taking f_c^2 (at the nucleon pole) to be[25] $0.079(\pm 0.001)$ and correcting it to $\mathbf{q}^2 = 0$ gives an apparent charged-pion coupling constant squared $f_c^2(\mathbf{q}^2 = 0)$ between 0.074 and 0.067, with 0.073 ± 0.001 preferred. This is in excellent agreement with the value of f_0^2 obtained by the Nijmegen group.

To finish we caution the reader against the casual interpretation that this interpretation of the Nijmegen work is so simple as to render it unimportant. As Ericson has stressed,[8] the effect of changing Λ from 1.3 GeV, as required in a boson-exchange picture of the N-N interaction, to 730 MeV is dramatic—particularly in the region 1.0 to 2.5 fm, which is important in calculating, e.g., nuclear binding energies. The result of Bergervoet *et al.* provides clear evidence that our understanding of the N-N system in that region is not yet complete.

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[a]Permanent address: Institute für Kernphysik, Kernforschungsanlage Jülich, D-5370 Jülich, West Germany.

[1]J. R. Bergervoet, P. C. van Campen, T. A. Rijken, and J. J. de Swart, Phys. Rev. Lett. **59**, 2255 (1987).

[2]T. A. Rijken, in Proceedings of the Twelfth International Conference on Few Body Problems, Vancouver, 1989 [Nucl. Phys. (to be published)].

[3]K. Brauer, A. Faessler, and E. M. Henley, Phys. Lett. **163B**, 46 (1985).

[4]T. A. Al-Aithan and Riazuddin, Phys. Rev. C **38**, 1822 (1988).

[5]A. W. Thomas, R. P. Bickerstaff, and A. Gersten, Phys. Rev. D **24**, 2539 (1981).

[6]R. Machleidt, K. Holinde, and Ch. Elster, Phys. Rep. **149**, 1 (1987).

[7]T. E. O. Ericson and M. Rosa-Clot, Nucl. Phys. **A405**, 497 (1983).

[8]T. E. O. Ericson, Prog. Part. Nucl. Phys. **11**, 245 (1982).

[9]H. Primakoff, in *Nuclear and Particle Physics at Intermediate Energies,* edited by J. B. Warren, NATO Advanced Study Institutes, Ser. B, Vol. 15 (Plenum, New York, 1976), p. 1.
[10]J. Gasser and H. Leutwyler, Phys. Rep. **87**, 77 (1982); J. Gasser, Ann. Phys. (N.Y.) **136**, 62 (1981).
[11]P. A. M. Guichon, G. A. Miller, and A. W. Thomas, Phys. Lett. **124B**, 109 (1983).
[12]A. Chodos *et al.*, Phys. Rev. D **10**, 2599 (1974).
[13]G. E. Brown and M. Rho, Phys. Lett. **82B**, 177 (1979).
[14]S. Théberge, A. W. Thomas, and G. A. Miller, Phys. Rev. D **22**, 2838 (1980); **23**, 2106(E) (1981).
[15]M. Beyer and S. K. Singh, Phys. Lett. **160B**, 26 (1985).
[16]U. G. Meissner *et al.*, Phys. Rev. Lett. **57**, 1676 (1986); W. Weise, in *Proceedings of the First Yukawa International Seminar,* edited by O. Otsubo and T. Suzuki [Prog. Theor. Phys. Suppl. **91**, 99 (1987)].
[17]N. Baker *et al.*, Phys. Rev. D **23**, 2499 (1981); K. Miller *et al.*, *ibid.* **26**, 537 (1982); T. Kitagaki *et al.*, *ibid.* **28**, 436 (1983).
[18]L. A. Ahrens *et al.*, Phys. Rev. D **35**, 785 (1987).
[19]EMC Collaboration, J. Ashman *et al.*, Phys. Lett. B **206**, 364 (1988).
[20]F. E. Close, University of Tennessee report, 1989 (to be published).
[21]D. Schütte and A. Tillemans, Phys. Lett. B **206**, 1 (1988).
[22]A. W. Thomas, Phys. Lett. B **126**, 97 (1983); Prog. Theor. Phys. Suppl. **91**, 204 (1987).
[23]L. L. Frankfurt, L. Mankiewicz, and M. I. Strikman, Leningrad report, 1989 (to be published).
[24]M. Strikman (private communication).
[25]O. Dumbrajs *et al.*, Nucl. Phys. **B216**, 277 (1983).