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MESON-BARYON FORM FACTORS: HARD OR SOFT?

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1 Introduction

Meson-baryon-baryon form factors (MBB) such as πNN, ΔNN (see Fig.1), and others are the basic ingredients of any microscopic calculations in nuclear physics in which meson degrees of freedom are taken into account explicitly. These form factors are introduced into the theory phenomenologically to overcome difficulties connected with the still unknown physics of strong interacting particles at short distances. For simplicity, we consider below the πNN-form factor.

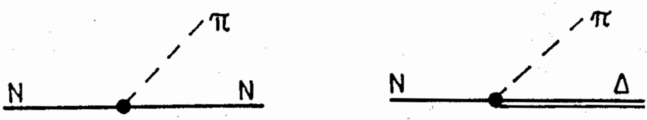

Fig.1 The πNN and $\pi N\Delta$ vertices

There are different parametrizations of the MBB-form factors such as: The monopole (M) form of the MBB-form factor

$$F_{\pi NN}^{(M)} \sim (1 + \frac{t}{\Lambda_M^2})^{-1}. \tag{1}$$

The dipole (D) form

$$F_{\pi NN}^{(D)} \sim (1 + \frac{t}{\Lambda_D^2})^{-2}, \tag{2}$$

and the exponential (E) form

$$F_{\pi NN}^{(E)} \sim exp(-\lambda t), \lambda \equiv \frac{1}{\Lambda_E^2}. \tag{3}$$

Here $t = -q^2$ is the invariant Mandelstam variable: $q = p' - p$ is the four-momentum transfer. The normalization of these form factors are fixed by the on-shell condition for the exchange particle

$$F(t = -m_\pi^2) = 1. \tag{4}$$

The cutoff mass parameter Λ is treated as a phenomenological parameter, and there are big uncertainties concerning its value that is extracted from different nuclear-physics processes. Schematically, these values can be refered to two classes: the "hard" and "soft" form factors. For the monopole form of the MBB-form factor, the "hard" form factors are determined by

$$\Lambda_M > 1\,GeV/c, \tag{5}$$

and for the "soft" form factor

$$\Lambda_M < 1\,GeV/c. \tag{6}$$

For explaining some fundamental nuclear physics phenomena such as NN-interaction within the framework of the one-boson exchange models [9],[10], [12], the hard form factors are used: $\Lambda_M \sim 1.2 - 1.4\,GeV/c$. The same form factors are usually used in the meson-exchange-current calculations , and also in the theory of pion-nucleus interaction developed within the many-body field theoretical framework (see, e.g. [31]).

On the other hand, in the theory of pion-nucleon interaction, the theory of the πNN-system (which we discuss below) the soft form factors seem to be more relevant. The question of the size of the form factor is related to the range of the pion-nucleon interaction. From the analysis of different nuclear reactions at intermediate energies (see, e.g.[6],[7], [8]) the soft cut-off mass parameter (smaller than $0.7\,GeV/c$) has been obtained.

The problem of the size of the MBB form factors comes well to the fore when a strong indication in favor of the soft form factors has been obtained [2], [3], [4] from deep inelastic lepton-nucleon scattering (DIS).

2 One-Pion Exchange and DIS

Originally, the idea to study one-meson exchange by the DIS process (see Fig.2) was proposed by Sullivan [1] in 1972. In this paper, it has been shown that in the Bjorken limit the pionic contribution to an antiquark distribution in the nucleon, $\bar{q}_N(x)$, is given by a pion momentum distribution $f_\pi(y)$ in the infinite-momentum frame and an antiquark distribution in the pion, $\bar{q}_\pi(x)$:

$$x\bar{q}_N(x) = \int_x^1 dy\, f_\pi(y)\frac{x}{y}\bar{q}_\pi(\frac{x}{y}) \tag{7}$$

where $f_\pi(y) = f_\pi^{(\pi NN)}(y) + f_\pi^{(\pi N\Delta)}(y)$. These functions are related to the vertex form factors $F_{\pi NN}$ and $F_{\pi N\Delta}$. For example,

$$f_\pi^{(\pi NN)}(y) \sim g_{\pi NN}^2 y \int_{t^{max}}^{\infty} dt \frac{t}{t+m_\pi^2}[F_{\pi NN}(t)]^2 \tag{8}$$

where t is the minus four-momentum square of the pion, $t^{max} = M_N^2 y^2/(1-y)$.

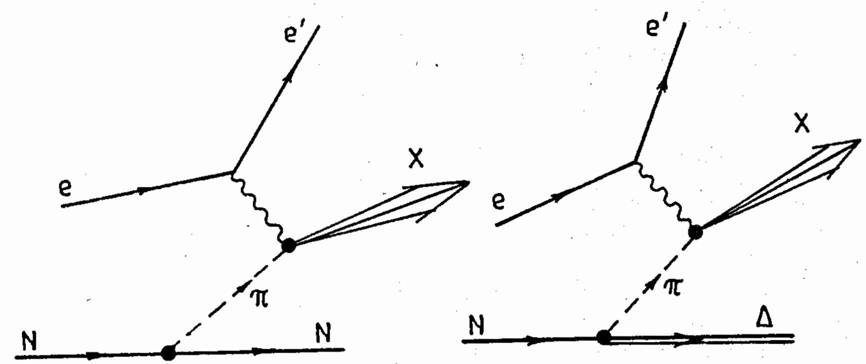

Fig.2 Pionic contributions in DIS from (a) πNN process and (b) $\pi N\Delta$ process

Integrating Eq.(7) over x we obtain the Sullivan formula in the integral form

$$\int_0^1 dx x \bar{q}_N(x) = \int_0^1 dz z q_\pi(z) \int_0^1 dy y f(y) . \tag{9}$$

There are experimental data on the pion and nucleon structure functions. The antiquark distribution $\bar{q}_\pi$ in the pion is available from the Drell-Yang experiments, and the sea antiquark distribution $\bar{q}_N$ is obtained from deep inelastic (anti)neutrino proton, deuterium and nucleus scattering. Using these, experimentally determined, pion and nucleon structure functions, in [2], [3], [4] the upper limits on the cut-off mass parameter of the πNN form factor have been obtained, which are presented in Table.1

Table 1. Upper bounds on the cut-off mass parameter of πNN form factor from DIS

$\Lambda(GeV/c)$	$Ref.$[2]	$Ref.$[3]	$Ref.$[4]	$Ref.$[5]
Λ_M	0.55	0.5	0.6	0.713
Λ_D	0.89	0.9	0.95	1.15
Λ_E	0.71	0.64	0.75	0.914

The cut-off mass parameters Λ_M , Λ_D and Λ_E, which correspond to different forms of the vertex functions (1) - (3), are related by the equation [4]

$$F^M(t_0) = F^D(t_0) = F^E(t_0) = 0.4 . \tag{10}$$

Solving this equations, one obtain the following relation among these parameters

$$\Lambda_M = 0.62\Lambda_D = 0.78\Lambda_E . \tag{11}$$

This relation provides independence of antiquark distributions obtained from Eq.(7) of the form of the πNN form factor.

The values for the cut-off parameter, presented in the last column of Table 1, have been obtained in [5], where the analysis of the Sullivan process was extended by taking into account effects of additional mesons including ρ, ω, K, and K^*. As it it seen from the Table 1, though for the dipole form factor the "hard" value has been obtained in [5], for the monopole cut-off parameter we obtain , using Eq.(11), the "soft" value (see (6)).

Summarizing, the results presented in Table 1 show that from DIS there is a strong indication that the πNN form factor is soft, i.e.

$$\Lambda_M < 0.8\, GeV/c .$$

3 Theory of pion-nucleon interaction

The range of the πN interaction has been a long-standing problem of nuclear pion physics (see, e.g. [30], [14]). In this section, we discuss the results of different approaches which are used for the description of the πN interaction at intermediate energies, such as the potential model, field theoretical approach based on the Chew-Low type equations, and the chiral bag models.

$*$ Potential models

Potential model for the πN interaction is widely used in pion-nucleus theory providing an effective tool for the off-energy shell extrapolation of the πN t-matrix.

There are a lot of separable potentials which describe well the on-shell data for six dominant s- and p-waves at energies below $300 MeV$. We also have now (see, e.g. [15], [17]) separable potentials which fit data for higher partial waves at energies up to $1 - 1.5\, GeV/c$. For the description of all partial waves other than P_{11}, a rank-one separable potential can be effectively used, i.e.

$$v_\alpha(k,k') \sim g_\alpha(k) g_\alpha(k') \tag{12}$$

where $\alpha = (l, j, I)$ label the quantum numbers of the partial channel, and the form factors

$$g_\alpha(k) \sim k^l (k^2 + \beta_\alpha^2)^{-(l+1)}. \tag{13}$$

The form factors obtained by fitting the data are usually soft [17]: $\beta_\alpha < 0.3 - 0.4\,GeV/c$. It is not surprising because for these channels the πN dynamics is determined mainly by the t-channel exchanges, and the range of the πN interaction is related to the mass of exchanged particle.

To describe the P_{11}-wave, one has to use at least a rank-two separable energy-dependent potential

$$v_{11} = f_0(k) \frac{1}{E - M} f_0(k') + g(k) \lambda g(k'). \tag{14}$$

The first term takes into account the contribution of the s-channel (nucleon) pole in the P_{11}-wave, and $f_0(k)$ is the πNN vertex function.

Therefore, the range of the πN interaction in the P_{11}-channel is determined by the range of the πNN form factor $F_{\pi NN}$. In [17] it has been shown that by fitting the data with the monopole form of the vertex function we obtain

$$\Lambda_M < 0.6 - 0.7\,GeV/c,$$

i.e., the soft form factor.

$*$ **Chew-Low type equations**

One of the main drawbacks of the potential model is that the crossing symmetry of the strong interaction is not taken into account. In [15], [16] the πN interaction has been studied within the framework of the Chew-Low model [13]. In this approach the basic equation for the πN t-matrix is crossing symmetric. In Ref.[15] the πNN form factor in the exponential form has been used, $F_{\pi NN} \sim exp(-k^2/\Lambda_E^2)$, and a good description of the P_{33} wave up to $\sim 1\,GeV/c$ has been obtained with $\Lambda_E \sim 0.8\,GeV/c$. This value corresponds (see Eq.(11)) to the monopole cut-off parameter

$$\Lambda_M \sim 0.6\,GeV/c.$$

$*$ **Nucleon structure and the πNN form factor**

In the last years, chiral bag models have attracted much interest due to their ability to incorporate quark degrees of freedom in the description of the pion-nucleon interaction [19], [20], [21], [22]. In these models the range of the πNN form factor is related to the size of the bag radius [19]

$$F_{\pi NN}(k) \sim \frac{j_1(kR)}{R} \sim exp(-\lambda k^2)$$

where $\lambda \approx 0.106 R^2$, or in terms of $\Lambda_E = (\lambda)^{-1/2}$

$$R \approx 1/0.33\Lambda_E. \tag{15}$$

Using the upper limit on the cut-off parameter $\Lambda_E < 1 GeV/c$ (see Table 1), we obtain the lower bound on the bag radius $R > 0.6 fm$, which excludes the concept of a little bag with a size of an order of $0.3 - 0.4 fm$ [20].

In recent years, a nonlinear model for mesonic fields which contains baryons as a topological soliton (the Skyrme model) has received much attention. Such an approach is motivated by the large-N_c expansion of QCD. This model allow a natural description of meson-baryon scattering in terms of quantum fluctuations of the meson field around the soliton background. Many phenomena in the pion-nucleon interaction at low and intermediate energies could be naturally understood (at least qualitatively) within the framework of this model (see, e.g. [23], [24], [25]).

The pion-nucleon form factor $F_{\pi NN}$ in this model is related to the baryon profile function as [24]

$$F_{\pi NN} \sim \int sinF(r)j_1(kr)r^2dr. \tag{16}$$

A typical value of the cut-off mass parameter of a monopole fit to the form factor is about $\Lambda_M \simeq 0.6\, GeV/c$.

In [26], an extended Skyrme model with explicit inclusion of ρ and ω mesons has been considered. The obtained value of the cut-off mass in this paper is about $0.9\, GeV/c$ in a monopole approximation which is larger than the upper bound obtained from DIS (see Table 1), but is still "soft".

4 Theory of the πNN system

In this section we consider models (see [18], [27], [28], [29]) that provide a simultaneous description of all the processes $NN \to NN, NN \to \pi NN, NN \to \pi d, \pi d \to \pi d$ and $\pi d \to \pi NN$. Theory of the πNN system is a basis for an extrapolation of the NN potential to energies above the pion production threshold. Theory of the πNN system is based on the Faddeev-type equations extended to the case where the number of particles is not conserved, and the coupling $NN \leftrightarrow \pi NN$ is provided by introducing the transition operators in terms of the πNN- and $\pi N\Delta$-vertices.

In a number of papers (see, e.g. [27]) it has been shown that the results of calculation of many observables in this approach are very sensitive to the range of the πNN and $\pi N\Delta$ form factors. Usually, a better description of the data is obtained by using a moderately soft form factors. A detailed study of sensitivity to the cut-off mass has been done by Lee and Matsuyama [29] within the framework of the unitary meson-exchange πNN model. It has been shown [29] that

using "hard" values for the πNN cut-off mass, one would not be able to reproduce the NN total reaction cross section and total polarization cross sections at energies up to $1\, GeV/c$. More or less good description is obtained for $\Lambda_M < 0.8\, GeV/c$.

5 Conclusion

* From the discussion presented in the foregoing section one can conclude that the soft pion-nucleon form factors are more relevant to the description of the pion-nucleon interaction at low and intermediate energies (up to $1\, GeV/c$).
** The values of the cut-off mass parameters of the MBB-vertices ($\Lambda_M < 0.8\, GeV/c$), which provides the best description of the data, are in agreement with the upper bounds obtained from DIS.

In the description of the NN-interaction within the framework of the one-boson exchange models (which reproduce the deuteron properties) the hard form factors are usually used. If we take seriously the concept of soft form factors in the low-energy nuclear physics, it is necessary to consider a possibility of constructing the NN interaction in terms of the soft form factors. This possibility has been considered in Refs.[11],[32] and has been discussed in the recent review [12].

In conclusion, the list of references is far from being complete, and the author apologizes if some of the important papers have not been reviewed in this short article.

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