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A study of the pion–nucleon coupling constant based on scattering length and effective range for both pseudovector and pseudoscalar

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ABSTRACT

In this study, we critically evaluate the Yukawa potential using the meson field theory in order to establish a relationship between the energy (MeV) for both neutron–proton and proton–proton which is pseudoscalar and pseudovector in the case of scattering field, similar in the effect range from experimental values of pion atoms. We also deduce the charged pion–nucleon coupling constant systematically and with statistical uncertainties. The result shows that both models display good agreement with the experimental values with a trend as the energy increases for both interactions' effective range on pseudovector (proton–proton) and pseudoscalar (neutron–proton) is at a smaller length. Similarly, low energy is recorded for the scattering length interaction. The charge pion–nucleon coupling constant is at values of $\frac{g_{\pi^\pm}^2}{4\pi} = 14.54$ and $\frac{g_{\pi^\pm}^2}{4\pi} = 14.52$ for both pseudovector and pseudoscalar, respectively. This shows that the electromagnetic interaction associated with the correction will likely be added or removed from the experimental values of the nuclear-Coulomb low-energy parameters of pp and np scattering

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1. Introduction

In nuclear and particle physics, we consider the pion–nucleon coupling constant as the fundamental physical quantity. This is set into a nuclei scale of interaction, along with the pion mass. Accordingly, Goldberger–Treiman established an important relationship in the field of particle physics in the following ways by conducting an important test of chiral symmetry where they found an error in the main obstacle in the accurate discussions of the correction to the pion–nucleon coupling constant relation, as predicted from the chiral symmetric splitting pion–nucleon–nucleon (NN) at about 1%–5%, to match this experimental difference on these quantities is established in the Goldberger–Treiman relation. Table 1 presents the recent situation with uncertainties as quoted by the authors. In the earliest 1980s, the pion–NN coupling constant was well known by different scholars. Let us look at the result of Koch and Pietarinen (1980), who estimated the value of the charged-pion coupling constant as $\frac{g_c^2}{4\pi} = 14.28.$ Beringer et al. (2012) deduced from π ± p scattering data; similarly, Babenko et al. (2009) obtained the value for a neutral pion coupling constant from their computation and experiment as $\frac{g_c^2}{4\pi} = 14.52$ for pp based on the forward dispersion relation.

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In addition to this, the question was eluted in the early 1990s from the results of the research papers published by the Nijmegen group (Stoks et al., 1993), Bergervoet et al. (1990) and Rahm et al. (2001). They reported small values based on energy-dependent partial wave analyses (PWA) of NN scattering data, with values of $\frac{g_0^2}{4\pi}=13.47$ and $\frac{g_c^2}{4\pi}=13.58$. On the other hand, the Virginia Tech group recorded a low value of $\frac{g^2}{4\pi}$ at about 13.7 from the analysis of both pion–nucleon coupling constant and NN data by employing the method of low energy-dependent PWA in the pion–neutron–proton sector. A similar value was recorded by Bugg (2004) with a value of 13.45. The analysis which is said to be the most recent was a drawback due to the joint analysis carried out by different researchers associated with a large database of many experiments with some data being rejected observing some criteria. It was noted that the statistical accuracy was very high, without systematic uncertainty. The Goldberger–Miyazawa–Oehme (GMO) was exalted wherein they used the sum rule Machleidt et al. (2000) done by several groups researcher's Arndt et al. (1994), Sliv et al. (1974), Ardnt et al. (1995). The forward scattering sum rule for *pp* scattering (Bergervoet et al. 1990) directly depends on the physical observability of governing principles. The result obtained from these determinations has not been subjected to any examination. The corrected result is given in Table 1. Is an erroneous input data based on erratum? This determination of the pion–nucleon is based on the extrapolation of experimental data of single energy backward differential *np* cross sections on the pion pole (Ericson et al., 1995; Rahm et al., 1998). This shows the systematic agreement between statistical and systematic uncertainties, but the uncertainty is said to be very large when compared to what can be achieved using the GMO sum rule. The result obtained from the extrapolation is recorded as 14.52, and that is what we used in describing the Yukawa potential to evaluate the low-energy charge dependency based on NN because this value is larger than those obtained from indirect methods. The problem associated with the determination which has recently been identified in a dedicated workshop (Arndt et al., 2004; Beringer et al., 2012; Rahm et al., 2001), as well as a conference workshop group (SLiv, 1974), helped to resolve Table 1. Some deduced values of the pion–NN coupling constant with quoted uncertainties are suggested by many authors.

Table 1. Some values of pion–NN coupling constant with quoted systematic uncertainty deduced by different authors (Ericson and Rosa-Clot, 1983).

Source	Year	System	$g_\delta^2(NN)/4\pi$
Karlsruhe-Helsinki	1980	πp	14.28
Bugg	2004	pp	14.52
Nijmegen	1993	pp, np	13.58
VPI	1994	pp, np	13.70
Nijmegen	1997	pp, np	13.54
Ardnt et al.	1995	$\pi^+ p$	13.45
VPI	1994	$GMO, \pi p$	13.75
Uppasala	1998	$np \to pn$	14.52
Babenko et al.	2009	πp	13.73
Rahm et al.	2001	$GMO, \pi^\pm p$	13.77
Ericson	1995	$GMO, \pi^\pm p$	14.17

This is inconsistent with the exact independent determination, leading directly to the primary observables and quantifiable systematic and statistical errors. The reason for this study is to demonstrate that recent experimental advances made by the GMO relation are suitable for the designed problem.

2. Materials and Method

In this study, we examine the pion–nucleon coupling constants for neutral and charged pions based on the data from the low-energy NN scattering semiphenomenological one-boson-exchange potential models, with various exchange mesons, which are frequently used to describe the NN interaction. In this method, the exchange of pions, which is light, determines primarily the long-range part of the NN potential, while the exchange of rho and Omega mesons, which is heavier, determines the interaction at intermediate and short distances, which is substantial at higher energies. In the situation where there are low energies, its effect extremely corresponds to long distances. The use of the most effective and efficient one—pion-exchange potentials—is optimal to describe the NN interaction. In respect to this circumstance and under some basic assumption that nuclear forces on the NN system at low energies are due primarily to exchange the virtual pion, we make use of the well-known

Yukawa potential and then follow the mesons field theory. Hulth´en and Sugawara, (1957), Sliv (1974), and Ericson and Weise, (1988) describe the NN interaction, given that we match the parameters of potential (i.e., its depth V_0 and range *R*) with low-energy parameters of NN scattering in the $^1S_0$ spin-singlet state. By introducing the parameters of the Yukawa potential for (pp) and neutron–proton (np) interactions with the equation that relates change deduced ($f^2_{\pi^\pm}$) and neutralized ($f^2_{\pi^0}$) pseudovector pion–nucleon coupling constants.

2.1. Meson field theory

According to the meson field theory, virtual pion in the nucleon is largely exchanged due to the strong nuclear interaction which is primarily determined by the long-range part of the NN interaction, and according to the NN potential, which follows the meson field theory, it is called the Yukawa potential which is written as follows:

$$V_Y(r) = -V_0 \frac{e^{-\mu r}}{\mu r} \tag{1}$$

where *r* is the distance between two nucleons and μ is the pion mass M_π given by the following equation:

$$\mu = \frac{M_\pi C}{\hbar} \tag{2}$$

where *C* is the speed of light and $\hbar$ is the reduced Planck constant. The nuclear force range *R* is coincident with the Compton wavelength of the pion.

The pseudovectors pion–nucleon coupling constant f_π is given by the simple Equation (5) as follows:

$$V_0 = m_\pi C^2 f_\pi^2 \tag{3}$$

Thus, the pion mass m_π and the pion–nucleon coupling constant f_π are basic characteristics of the pion–nucleon interaction, which is of paramount importance in the studying of NN and pion–nucleon interactions (Machleidt et al., 2000; Miller et al., 1990). The pseudovector coupling constant for neutral ($f^2_{\pi^0}$) and charged ($f^2_{\pi^\pm}$) pions are related to the pseudoscalar coupling constants ($g^2_{\pi^0}$) and ($g^2_{\pi^\pm}$) by the following equations:

$$g^2_{\pi^0} = \left(\frac{2m_p}{m_{\pi^\pm}}\right)^2 f^2_{\pi^0} \tag{4}$$

$$g^2_{\pi^\pm} = \left(\frac{m_p + m_n}{m_{\pi^\pm}}\right)^2 f^2_{\pi^\pm} \tag{5}$$

where m_p and m_n are the masses of proton and neutron, respectively, and $m_{\pi^\pm}$ is the charged pion mass.

The experimental values of the proton, neutron, pion mass, neutral pion mass, and $\hbar C$ are given as follows:

$$m_p = 938.272046\,\mathrm{MeV/C^2} \tag{6}$$

$$m_n = 939565379\,\mathrm{MeV/C^2} \tag{7}$$

$$m_{\pi^0} = 134.9766\,\mathrm{MeV/C^2} \tag{8}$$

$$m_{\pi^\pm} = 139.57018\,\mathrm{MeV/C^2} \tag{9}$$

$$\hbar C = 197.3269718\,MeV \tag{10}$$

All the values in Equations (6–10) were obtained from the compilation of the particle data group (24). Exchange of the neutral pion led to two charged protons' interaction according to Equations (2 and 4). The parameters V_0^{PP} and μ_{pp} of the Yukawa potential (1) are determined by the neutral–pion mass m_{π^0} and the coupling constant f_{π^0}. But for neutron–proton interaction, both neutral and charged pions are exchanged. If the potential can be determined by using 3, then the average pion mass values are given as follows:

$$\overline{m_\pi} = \frac{1}{3}\left(m_{\pi^0} + 2m_{\pi^\pm}\right) \tag{11}$$

And the pion–nucleon coupling constant is

$$\overline{f_\pi^2} = \frac{1}{3}\left(f^2_{\pi^0} + 2f^2_{\pi^\pm}\right) \tag{12}$$

To determine the parameters of the potential in 1, we will employ the data for the interactions of the two nucleons at the lowest energies in the $^1S_0$ spin-singlet state. Furthermore, we will evaluate proton–proton parameters μ_{pp} and V_0^{PP} based on the scattering length a_{pp} and the effective range r_{pp}. In doing this, the electromagnetic interaction associated with correction will be removed from the experimental values of the nuclear-Coulomb low-energy parameters of pp scattering. After the removal of the corrections, the values of the purely nuclear scattering length a_{pp} and effective range r_{pp} for proton–proton scattering becomes (4) as follows:

$$a_{pp} = -17.3 \tag{13}$$

$$r_{pp} = 2.85 \tag{14}$$

By employing the variable-phase approach (Babikov, 1976) and the value of pp scattering parameters (Bugg et al., 1973; Dumbrajs et al., 1983), we obtain the following results for the parameter of the Yukawa potential for proton–proton scattering as follows:

$$\mu_{pp} = 0.8393 \tag{15}$$
$$V_0^{pp} = 44.8295 MeV \tag{16}$$

From Equations (6, 8, 9, and 16), the mass and the pion–nucleon coupling constant for the neutral pion in the case of the Yukawa potential for proton–proton interaction are obtained as follows:

$$m_{\pi^o}^{Y} = 165.6108 MeV / C^2 \tag{17}$$
$$\left(f_{\pi^o}^{Y}\right)^2 = 0.2707 \tag{18}$$

This is much greater than the experimental values:

$$m_{\pi^0} = 134.9766 MeV / C^2 \tag{19}$$
$$\left(f_{\pi^0}^2\right) = 0.0749 \tag{20}$$

Thus, we have the following:

$$m_{\pi^o}^{Y} = C_{m\pi} m_{\pi^0} \tag{21}$$
$$\left(f_{\pi^0}^{y}\right)^2 = C_{f_\pi} f_{\pi^0}^2 \tag{22}$$
$$C_{m_\pi} = 1.2270 \tag{23}$$
$$C_{f_\pi} = 3.6142 \tag{24}$$

We can say that a similar relationship exists in Equations (20 and 22), which holds for the charged pion mass and charged pion–nucleon coupling constants. Hence, the average pion mass. Because of this, it can be shown that the average pion–nucleon coupling constants are $C_{m\pi^0} = C_{m\pi^\pm} = C_{\overline{m}_\pi}$ and $C_{f\pi^0} = C_{f\pi^\pm} = C_{\overline{f}_\pi}$. It can be shown that the neutron–proton parameters μ_{np} and V_0^{np} of the potential in Hulth´en and Sugawara (1957) study is related to analogous proton–proton interaction parameters μ_{np} and V_0^{np} by the following equations:

$$\mu_{np} = \frac{\overline{m}_\pi}{m_{\pi^0}} \mu pp \tag{25}$$

$$V_0^{np} = \frac{\overline{m}_\pi}{m_{\pi^0}} \frac{\overline{f}_\pi^2}{f_{\pi^0}^2} V_0^{pp} \tag{26}$$

From Equations (8 and 9), the ratio of the average pion mass $\overline{m}_\pi$ to the neutral pion mass m_{π^0} is given as:

$$\frac{\overline{m}_\pi}{m_{\pi^0}} = 1.0227 \tag{27}$$

By using Equations (4, 25, and 26) and the experimental value of the singlet up scattering length for the $^1S_0$ state (Sliv, 1974) and (Bugg, 2004).

$$a_{np} = -23.71 \tag{28}$$

The following values are for the parameters:

$$\mu_{np} = 0.8584 \tag{29}$$
$$V_0^{np} = 48.0742 MeV \tag{30}$$

The effective range r_{np} found np scattering the Yukawa potential with the parameter values as follows (Babenko and Petrov 2007; Babenko and Petrov, 2010):

$$r_{np} = 2.70 \quad \text{... (31)}$$

2.2. Experimental value

$$r_{np} = 2.70 \tag{32}$$

The values of the singlet np scattering length in Sliv (1974) and the effective range (Hackenburg, 2006) are in very good agreement with the values of $a_{np} = -23.7154$ and $r_{np} = 2.706$ that were obtained (Babenko and Petrov, 2007; Babenko and Petrov, 2010) by using the experimental values of the np-scattering cross-section and the experimental values of the deuteron characteristics. Thus, the use of experimental values of the neutral and charged pion masses in Limkaisang et al. (2001) lead to a consistent description of experimental data on proton–proton and neutron–proton scattering in the region of low energies.

From Equations (26 and 30), we can obtain an important equation that relates the pseudovector changed and neutral pion–nucleon coupling constants as follows:

$$f_{\pi^\pm}^2 = \frac{1}{2}\left(\frac{3V_0^{np}}{V_0^{pp}} \frac{\mu_{pp}}{\mu_{np}} - 1\right) f_{\pi^0}^2 \tag{33}$$

The neutral pion–nucleon coupling constant together with the parameters of proton–proton scattering (Koch and Pietarinen, 1980; Stoks et al., 1993), the parameters of neutron–proton scattering in Bugg (2004) and Babenko (2007), with the pseudovector charged pion–nucleon coupling constant obtained the following:

$$f^2_{\pi^\pm} = 0.0804 \quad (34)$$

From Equations (4 and 5), and taking into account the pseudovector coupling constants for the neutral pion (Baru et al., 2011), the charged pion (Dumbrajs et al., 1983), the proton and neutron masses (Blomgren, 2000), and the charged pion mass (Limkaisang et al., 2001), the values of pseudoscalar pion–nucleon coupling constants obtained:

$$\frac{g^2_{\pi^0}}{4\pi} = 13.49 \quad (35)$$

$$\frac{g^2_{\pi^\pm}}{4\pi} = 14.54 \quad (36)$$

Similar to the value in Swart et al. (1999), the pseudoscalar charge pion–nucleon coupling constant is found to be perfectly in agreement with the experimental coupling constant.

$$\frac{g^2_{\pi^\pm}}{4\pi} = 14.52 \quad (37)$$

2.3. Uppsala neutron research group (Blomgren, 2000)

The values obtained in the recent study for the pion–nucleon coupling constant sizably differed from the value of the neutral pion–nucleon coupling constant in Arndt et al. (2006). There is a 6.95% difference which is indicatively the substantial charge dependence of the pion–nucleon coupling constant.

The nuclear forces in the NN system at low energies were primarily to exchange virtual pions. Thus, we established relationships between quantities that characterize the pion–nucleon and NN interactions. We have deduced the equation that relates pseudovector charged and mental pion–nucleon coupling constant to the depth of the potentials that describe the np and *pp* interactions by using the values of $a_{pp} = 17.2$ and $r_{pp} = 2.849$ currently recommended for the purely nuclear *pp* scattering length and effective range. The experimental value of $a_{pp} = -23.71$ for the singlet *np* scattering length and the values of $\frac{g^2_{\pi^0}}{4\pi}$=13.56 (13) for the neutral pion–nucleon coupling constant that is pseudoscalar. The value obtained is $\frac{g^2_{\pi^\pm}}{4\pi} = 14.54$ for the charged pion nucleon coupling constant. The experimental values of $\frac{g^2_{\pi^\pm}}{4\pi} = 15.51$ and $\frac{g^2_{\pi^\pm}}{4\pi} = 17.73$ for the case of neutron–proton are closely the same as the experimental values of $\frac{g^2_{\pi^\pm}}{4\pi} = 14.52$ and $\frac{g^2_{\pi^\pm}}{4\pi} = 14.74$ and with the average value of $\frac{g^2_{\pi^\pm}}{4\pi} = 14.28$. At the same time, we obtained an odd value with $\frac{g^2_{\pi^\pm}}{4\pi} = 13.54$, which was found by using the NN scattering data and the value of $\frac{g^2_{\pi^\pm}}{4\pi} = 13.76$ computed from data on πN scattering. It is worth noting, however, a small value of pion–nucleon coupling constant as $\frac{g^2_{\pi^0}}{4\pi} = 14.49$ results in the weakening of the

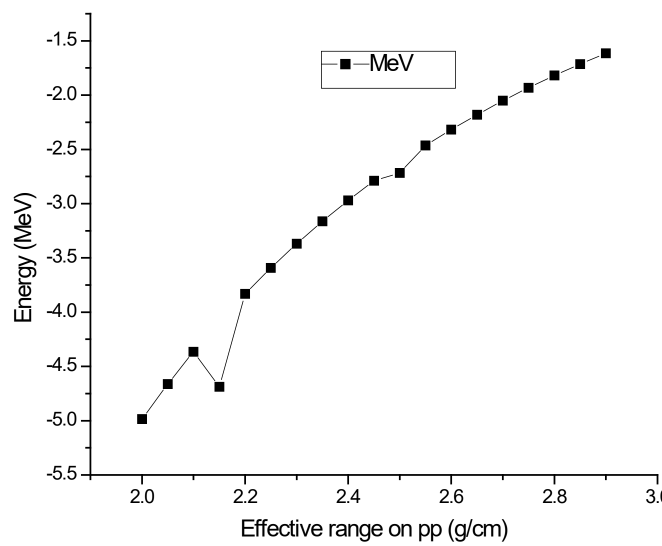

Figure 1. Plots of energy and effective range based on proton–proton.

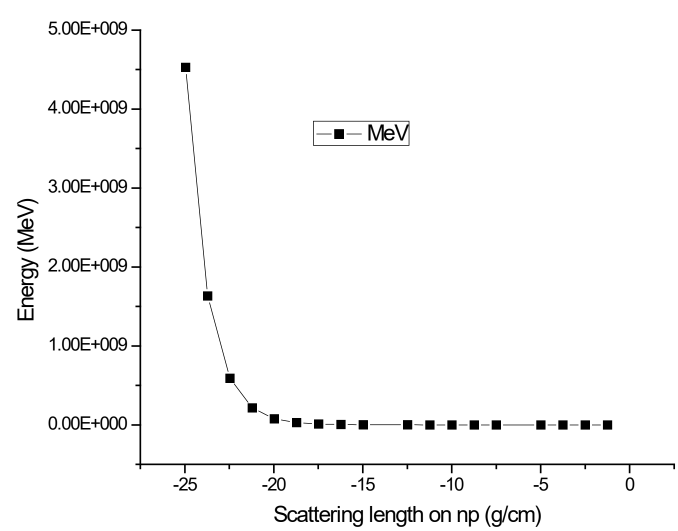

Figure 2. Plots of energy and pure nuclear scattering length.

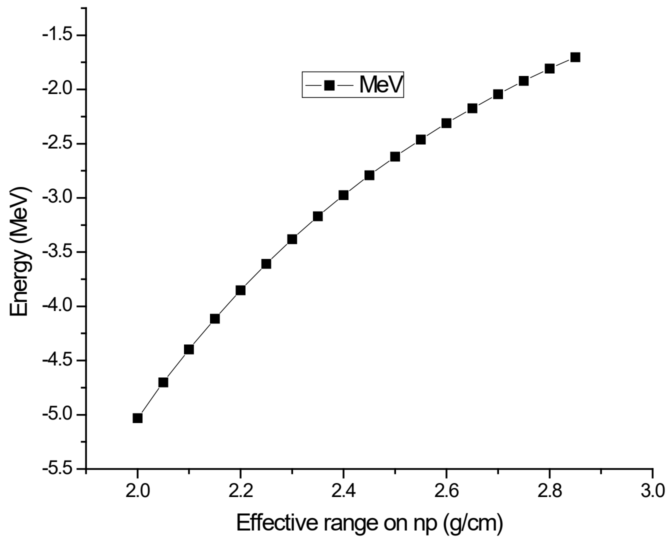

Figure 3. Plots of energy with effective range on neutron–proton.

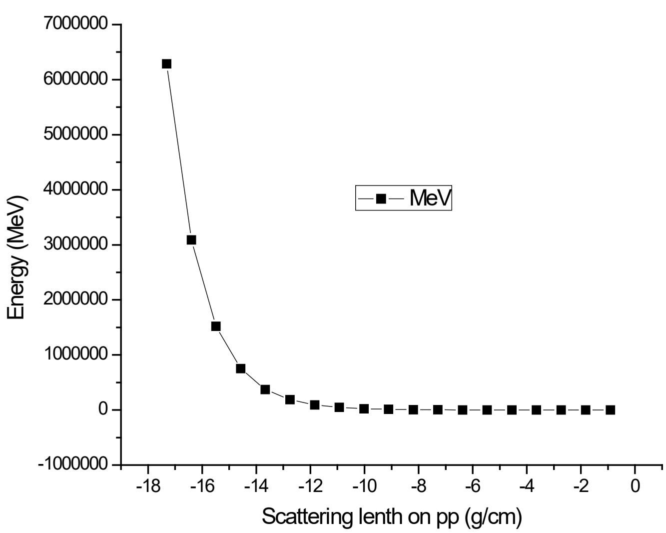

Figure 4. Plots of energy with pure nuclear scattering length on neutron–proton.

neutron–proton potential and to the absolute value of the singlet *np* scattering length which is underestimated as compared with the experimental value of $|a_{pp}| = 23.70$.

Figures 1–4 show the relationship between pion and nucleon coupling constant based purely on nuclear scattering length a_{pp}, a_{np}, and effective range r_{pp}, r_{np} on the Yukawa potential.

3. Conclusion

The results show a substantial charge dependence of the pion–nucleon coupling constant, accompanied by low-energy pion–nucleon and NN parameters. We conclude that there is the desecration of the charge independence of nuclear forces as a result of the primary difference in mass and pion–nucleon coupling constants associated with the neutral and charged pions. The energy deduced from the Yukawa potential using the meson field theory gives a high energy at a short (small) scattering length and effective range. On the other hand, little or low energy is obtained at a greater length for both scattering length and effective range. The result obtained from the study shows a violation of nuclear forces on the charge independence due to difference in mass between the neutral and charged pion, with a value of 3.35% difference in mass and 6.99% difference in pion–nucleon coupling between the neutral and charged pion. This also leads to proton–proton (*pp*) and neutron–proton (*np*) scattering lengths with a value of $\Delta aCIB \equiv app - anp = 6.39$, which is about 29.99% in relative units, and the difference in the effective range for proton–proton (*pp*) and neutron–proton (*np*) scattering is $\Delta rCIB \equiv rpp - rnp = 0.149$.

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