Recent Determinations of the πNN Coupling Constant and Deuteron Properties

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We examine the deuteron properties using the new value for the πNN coupling constant, $g_\pi^2/4\pi = 13.3 \pm 0.3$, which has been obtained in a recent analysis of $\pi^\pm p$ data and is about 7% smaller than earlier determinations. We find that this value is at variance with the deuteron properties if the strong empirical (Höhler-Pietarinen) ρ coupling is assumed which, in fact, is used in almost all modern realistic meson-theoretic models for the NN interaction. Within such models, a minimum of 13.9 for $g_\pi^2/4\pi$ is required, especially for the correct description of the deuteron quadrupole moment.

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In a recent analysis of the available $\pi^\pm p$ data below 2 GeV, Arndt *et al.*[1] have redetermined the value of the charged-pion–nucleon coupling constant. They find $g_c^2/4\pi = 13.31 \pm 0.27$.[2] About a decade ago, Koch and Pietarinen[3] had obtained $g_c^2/4\pi = 14.28 \pm 0.18$ in a similar analysis. In Ref. 1, the large discrepancy between the two results (4 standard deviations) is attributed to a 50% increase in the elastic $\pi^\pm p$ database below 600 MeV since 1983, due to the addition of high-precision data, which were not available to Koch and Pietarinen at the time of their analysis.

In recent years, the Nijmegen group has analyzed pp data below 350-MeV laboratory energy to determine the $\pi^0 pp$ coupling constant $g_0^2/4\pi$. Their analysis of 1987 yielded the value of 13.11 ± 0.11.[4] In 1990, the Nijmegen group obtained 13.55 ± 0.13.[5] Both results are substantially below the value of 14.52 ± 0.40 determined by Kroll[6] in 1981, who analyzed pp scattering data in terms of forward dispersion relations.

The new values for the charged and neutral πNN coupling constants are sufficiently close to each other to render speculations about large charge-independence breaking in the πN and NN systems obsolete (at least, for the time being). It is, however, a nontrivial fact that these new values are about 7% below earlier determinations. It should also be noted that in almost all models for the nucleon-nucleon (NN) interaction constructed during the past twenty years, the large value ($g_\pi^2/4\pi \approx 14.4$) is used, consistent with the determinations of about a decade ago.

Since the mid 1950s, it is well established[7] that the pion is responsible for the long-range tensor component of the nuclear force, which is evidenced most convincingly in the properties of the deuteron.[8] In particular, the quadrupole moment of the deuteron (Q_d) and the asymptotic D/S-state ratio (A_D/A_S) are a direct consequence of the tensor component of the nuclear force. These properties are determined experimentally with an uncertainty of less than 2%. Modern realistic models for the NN interaction reproduce, in general, the deuteron properties within this uncertainty. Therefore, a substantial change in the value for the pion coupling (of about 7%) raises the question of whether the deuteron properties can still be precisely understood in the conventional way. It is the purpose of this Letter to investigate this question.

In the first step of our study, we have taken several modern realistic NN potentials and changed the pion-nucleon coupling constant to the new value $g_\pi^2/4\pi = 13.3$. The NN interactions we consider are the full Bonn model,[9] the relativistic one-boson-exchange potential (OBEP) of Ref. 10, and the Paris potential.[11] (Other potential models will be discussed below.) Originally, all three models used $g_\pi^2/4\pi = 14.4$. Changing the pion-exchange contribution affects the predictions for the deuteron binding energy to which all NN interactions are fitted. Thus, we first refit the deuteron binding energy by readjusting the appropriate parameter which controls the intermediate-range attraction in the model (by just a few percent). After this, we calculate Q_d and A_D/A_S.

The results of this first step of our investigation are summarized in Table I. In the upper half of the table, we recall the predictions by the original versions of the potentials. It is seen that all models explain the quadrupole moment well within the given uncertainty. Note that the predictions for Q_d are based on the impulse approximation and do not include the meson-current contributions (MCC). Thus, we have corrected the (very precise) experimental value for Q_d of 0.2859(3) fm^2 (Ref. 12) for the MCC, which are 0.009(5) fm^2 according to the calculations by Hadjimichael[13] and Kohno.[14] The large uncertainty in the MCC is due to the model dependence of the deuteron wave function and to ambiguities in the evaluation of the MCC.

The asymptotic D/S-state ratio of the deuteron is overpredicted by all (original) models as compared to the most recent experimental value by Rodning and Knutsen[15] of 0.0256(4). [Note that in the early 1980s, the experimental value for A_D/A_S was believed to be 0.0264(3).[16]]

Our results using $g_\pi^2/4\pi = 13.3$ in the three NN models under consideration are shown in the middle part of Table I. It is seen that there is now a clear disagreement between theory and experiment for Q_d as well as A_D/A_S.

TABLE I. Deuteron properties as predicted by various models for the NN interaction. In rows 2–5, we give the πNN coupling constants and the predictions for the deuteron properties (quadrupole moment Q_d, asymptotic D/S-state ratio A_D/A_S, D-state probability P_D) by the original versions of the models. Rows 6–8 contain the predictions by these models when $g_\pi^2/4\pi=13.3$ is used. The last two rows give the minimal value for $g_\pi^2/4\pi$ required to reproduce Q_d and A_D/A_S within the given uncertainty. The column labeled "Average" displays the rounded average of the predictions. Figures in parentheses after a value give the uncertainty in the last digit.

	Bonn[a]	OBEP[b]	Paris[c]	Average	Experiment
		Original model			
$g_\pi^2/4\pi$	14.40	14.40	14.43		
Q_d (fm^2)	0.2807	0.2782	0.2791	0.279(2)	0.277(5)[d]
A_D/A_S	0.02668	0.02645	0.02608	0.0264(3)	0.0256(4)[e]
P_D (%)	4.25	4.99	5.77		
		Using $g_\pi^2/4\pi=13.3$			
Q_d (fm^2)	0.2624	0.2585	0.2618	0.261(2)	0.277(5)[d]
A_D/A_S	0.02493	0.02479	0.02439	0.0247(3)	0.0256(4)[e]
P_D (%)	3.68	4.30	5.05		
		$g_\pi^2/4\pi$ required for			
$Q_d=0.272$ fm^2	13.88	14.05	13.97	14.0(1)	
$A_D/A_S=0.0252$	13.47	13.57	13.84	13.6(2)	

[a]Full Bonn model (Ref. 9).
[b]Relativistic one-boson-exchange potential (Ref. 10).
[c]Paris potential (Ref. 11).
[d]Corrected for MCC (see text).
[e]From Ref. 15.

We have also calculated the minimum value for the πNN coupling constant required to explain the deuteron properties within the given uncertainty. For this we choose the coupling constant such that the lower limit within the given uncertainty is reproduced (i.e., 0.272 fm^2 for Q_d and 0.0252 for A_D/A_S).

For this minimal πNN coupling constant we obtain the following: $g_\pi^2/4\pi=14.0\pm0.1$ with regard to the quadrupole moment and $g_\pi^2/4\pi=13.6\pm0.2$ with regard to the asymptotic D/S-state ratio (the errors refer to the model dependence). Thus, the result of this part of our study is that the pion coupling constant required to correctly describe the quadrupole moment of the deuteron is in clear disagreement with the new empirical value; in fact, it is off by 2 standard deviations. For A_D/A_S, the required πNN coupling is closer to the new value (just 1 standard deviation off). Though we certainly trust the latest experimental value for A_D/A_S on which our discussion is based, we note that this value is lower than any of the numerous earlier determinations.[17] A lower limit of 0.0256 for A_D/A_S would imply a minimal pion coupling of 13.9, consistent with the results for Q_d.

We stress again that the deuteron properties under consideration are due exclusively to the nuclear tensor force. It is now important to note that besides the pion, also the ρ meson contributes to the tensor force. The tensor component created by ρ exchange is of opposite sign and of shorter range (due to its larger mass) as compared to the pion contribution (thus, reducing the tensor component at short internucleonic distances).

The coupling of ρ mesons to nucleons is commonly described by the Lagrangian density

$$\mathcal{L}_{\rho NN}=g_\rho\bar\psi\gamma^\mu\psi\phi_\mu^{(\rho)}+\frac{f_\rho}{4M}\bar\psi\sigma^{\mu\nu}\psi(\partial_\mu\phi_\nu^{(\rho)}-\partial_\nu\phi_\mu^{(\rho)}), \quad (1)$$

where ψ denotes the nucleon and $\phi_\mu^{(\rho)}$ the meson field; M is the nucleon mass. It is generally believed that the tensor coupling constant f_ρ is much stronger than the vector coupling constant g_ρ, and it is customary to state this fact in terms of the ratio $\kappa_\rho\equiv f_\rho/g_\rho$. There is a history concerning the value for κ_ρ. Originally, it was assumed that κ_ρ has the value implied by the vector-meson-dominance model (VDM) for the nucleon electromagnetic form factor, that is, 3.7. In 1975, Höhler and Pietarinen[18] determined κ_ρ in a dispersion-theoretic analysis and found 6.6 ± 1.0. This value was confirmed by Grein in 1977,[19] who obtained $\kappa_\rho=6.0$.

Since 1976, almost all realistic models for the NN interaction use the Höhler-Pietarinen value for κ_ρ, which implies a large tensor force contribution from the ρ meson (reducing the pion contribution, particularly at short ranges). For example, in the full Bonn model[9] and in the OBEP model[10] $\kappa_\rho=6.1$ is used; for the Paris potential[11] $\kappa_\rho=6.6$ is implied.

In the second step of our study, we have investigated the relevance of the ρ contribution for the present issue.

TABLE II. Deuteron properties as predicted by models for the NN interaction using a weak ρ coupling. For Bonn and OBEP the VDM value $\kappa_\rho = 3.7$ is used. The Paris results are estimates (see text). For further explanations, see legend of Table I.

	Bonn (VDM)	OBEP (VDM)	Paris (VDM)	Reid[a]	Average	Experiment
			Using $g_\pi^2/4\pi = 13.3$			
Q_d (fm^2)	0.2707	0.2658	[0.2691]	0.2699	0.269(2)	0.277(5)
A_D/A_S	0.026 03	0.025 57	[0.025 17]	0.025 15	0.0255(4)	0.0256(4)
P_D (%)	4.60	5.29		6.12		
			$g_\pi^2/4\pi$ required for			
$Q_d = 0.272$ fm^2	13.38	13.65	[13.49]	13.45	13.5(1)	
$A_D/A_S = 0.0252$	12.78	13.05	[13.32]	13.33	13.1(2)	

[a]Reid soft-core potential (Ref. 20).

For this purpose, we have weakened the ρ contribution by choosing the VDM value $\kappa_\rho = 3.7$ in the full Bonn and in the OBEP model (and using $g_\pi^2/4\pi = 13.3$ at the same time). The deuteron properties predicted by these models (Table II) are now close to experiment.

In Table II, we also include results which are obtained by using the Reid soft-core potential with a pion coupling of 13.3. (The original Reid soft-core potential uses $g_\pi^2/4\pi = 14$, and predicts $Q_d = 0.2796$ fm^2 and $A_D/A_S = 0.026\,22$.) Note that the Reid potential does not have an explicit ρ meson contribution; however, its tensor force component contains a term with the range of four pion masses which is of opposite sign as compared to the pion contribution and may be interpreted as a weak ρ contribution.

In the parametrization of the Paris potential, the ρ contribution cannot be clearly identified. Therefore, the Paris results in Table II are estimates which are obtained by applying the differences between the weak and strong ρ OBEP predictions to the Paris results of Table I (using $g_\pi^2/4\pi = 13.3$).

As before, we also give the minimal $g_\pi^2/4\pi$ which reproduces Q_d and A_D/A_S within the given uncertainties. This time, we obtain $g_\pi^2/4\pi = 13.5 \pm 0.1$ as necessary for the quadrupole moment and $g_\pi^2/4\pi = 13.1 \pm 0.2$ as necessary for the asymptotic D/S-state ratio (again, errors reflect model dependence). Notice that both of these values are now in agreement with the new empirical value.

A crucial question in our investigation is how small the πNN coupling constant can be and still be consistent with the deuteron properties and other known facts. To be conclusive, one must take into account all uncertainties in our knowledge of the nuclear force which have bearings on the tensor component. Among those, the πNN form factor is important. We have investigated the possibility of a "harder" form factor and found that this does not alter our conclusions concerning the minimal $g_\pi^2/4\pi$ beyond those drawn from the full-Bonn-model results. We also see little hope that the inclusion of subhadronic degrees of freedom may lower the minimal $g_\pi^2/4\pi$ since quark-bag form factors already lead to extremely small predictions for Q_d and A_D/A_S when the large value of 14.4 is used for the πNN coupling constant.[10]

Furthermore, one should also consider other modern realistic potentials.[21-23] The results to be expected from the variation of the pion coupling constant in other potentials can be estimated fairly accurately. In Table III we give the rate of change of Q_d and A_D/A_S as functions of $g_\pi^2/4\pi$ for the four potentials for which we have performed rigorous calculations. It is seen that these rates are very similar in all cases. We also found that, to a very good approximation, Q_d and A_D/A_S depend linearly on $g_\pi^2/4\pi$. These facts allow for reliable estimates of the predictions by other models when the pion coupling is changed. For the potentials of Refs. 21–23, we found these estimates to be in agreement with our above re-

TABLE III. Rate of change of Q_d and A_D/A_S as a function of $g_\pi^2/4\pi$ for various NN interaction models.

	Bonn	OBEP	Paris	Reid	Average
$\frac{\Delta Q_d}{\Delta(g_\pi^2/4\pi)}$ (fm^2)	0.0166	0.0179	0.0153	0.0139	0.0159
$\frac{\Delta(A_D/A_S)}{\Delta(g_\pi^2/4\pi)}$	0.001 59	0.001 51	0.001 50	0.001 53	0.001 53

sults. In particular, the minimal $g_\pi^2/4\pi$ obtained from any of these potentials is not smaller than what we found above. Because of space limitations, a more detailed discussion of these and other aspects which we have investigated cannot be given here and will be reported elsewhere.

In conclusion, the presently best empirical values for the πNN and the ρNN coupling constants are in disagreement with the deuteron properties. Strictly speaking, this implies that our traditional and well-established understanding of the deuteron is called into question. However, we feel that, in the present stage, one should not (yet) jump at far-reaching conclusions. In fact, it is likely that simply the errors in the new determinations of the πNN coupling constants are underestimated. This conjecture is supported by the fact that in previous analyses the errors must have definitely been underestimated. For example, the value for $g_0^2/4\pi$ from the Nijmegen *pp* analysis of 1987 and the one obtained by the same group three years later are off by 3 standard deviations; this suggests that the error for at least one of the two determinations must have been much too small. Similar observations can be made for the determinations from $\pi^\pm p$ elastic-scattering data. The results from the Koch and Pietarinen analysis of 1980 and the new analysis by Arndt *et al.* are off by 4 standard deviations.

In view of the above history, it may be reasonable to propose that the discrepancy we have pointed out could be resolved as a simple matter of empirical error. Therefore, we strongly suggest that the *pp* and the $\pi^\pm p$ data be reanalyzed by independent groups. Furthermore, it may also be appropriate to critically review the dispersion-theoretic analysis, as well as the database, from which the ρ coupling was determined. (In the Höhler-Pietarinen analysis[18] the πNN coupling constant is an input parameter for which the large Koch-Pietarinen[3] value of 14.28 is used.) On the theoretical side, efforts should be undertaken to reduce the uncertainties affecting present evaluations of the meson-current contributions to the deuteron quadrupole moment.

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