Nucleon-nucleon pion exchange tested in three-body reactions

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

L. Mathelitsch and J. Pauschenwein
Institute for Theoretical Physics, University of Graz, Universitätsplatz 5, A-8010 Graz, Austria
(Received 8 September 1992)

Variants of a one-boson-exchange potential are applied to elastic nucleon-deuteron and electron-deuteron scattering. The models differ with respect to the treatment of the pion-nucleon vertex, where either a small coupling constant or a soft form factor is employed. We find that these variations do not affect Nd observables, but that they have a sizable effect on ed quantities via exchange currents of the pion. Taking into account also exchange currents of the π' reduces the effect to a large extent.

PACS number(s): 21.30.+y, 13.75.Cs, 25.30.Bf, 21.45.+v

I. INTRODUCTION

The findings of the Nijmegen group [1] and of Arndt *et al.* [2] that the pion-nucleon (πN) coupling constant should have a value of approximately 5% less than the hitherto advocated number was a surprise, and it should have far-reaching consequences. For example, Machleidt and Sammarruca [3] have shown that such a low coupling constant causes trouble in reproducing the deuteron properties with a one-boson-exchange (OBE) model. Ericson [4] pointed out that it should also be crucial for the threshold photoproduction of charged pions, where the pertinent cross sections are proportional to the square of the πN coupling constant. On the other hand, Timmermans, Rijken, and de Swart [5] claim that some nucleon-antinucleon ($N\bar{N}$) data can be better reproduced with a small πN coupling constant.

The last conclusion was not confirmed in a recent paper by Haidenbauer, Holinde, and Thomas [6]. They constructed two variations of their (energy-dependent) OBE potential [7], one with the above suggested small πN coupling constant and one with a soft πN form factor, while keeping the former, larger value of the coupling constant. Furthermore, in order to conclude on a more general basis, an alternative set of NN potentials derived from an instantaneous interaction model [8] was considered. Haidenbauer, Holinde, and Thomas found that a comparably good overall description of NN phases is obtained with all four models. For low-energy proton-proton (pp) scattering, where new and very accurate data are available, both a small coupling constant and a soft form factor improve the fit. The study of $N\bar{N}$-scattering data did not yield any evidence to favor or discriminate any of the models. Therefore, Haidenbauer, Holinde, and Thomas suggested that further investigations should be done before drawing a final conclusion.

All above-mentioned investigations were done on the two-body level. In order to gain additional information it would be interesting to apply the potentials of Ref. [6] to few-body systems, which allow one to test not only the on-shell but also the (half-)off-shell component of the interaction. Therefore we performed calculations on elastic nucleon-deuteron (Nd) and electron-deuteron (ed) scattering. The interesting questions are whether the different potentials yield distinguishable results with respect to experimental data and error bars and whether such results could allow conclusions on the underlying pion-exchange mechanism.

The reasons for the choice of these two specific few-body systems are the following: Although recent three-nucleon calculations established a nice overall agreement between experimental data on Nd scattering and corresponding theoretical predictions [9, 10], there are a few but significant discrepancies. This concerns, above all, the nucleon analyzing power A_y at low energies. Witala and Glöckle [11] showed that slightly different values for the NN triplet-p phase shifts can improve the situation. Since also the models of Haidenbauer, Holinde, and Thomas exhibit variations in the p waves of the same order of magnitude, the question arises if an improvement on A_y can be achieved with them.

Electron scattering has the advantage that it gives a "clearer" picture of the deuteron because the system under study is not disturbed by a strong interaction with the probing particle. Since accurate data exist up to a high momentum transfer [12–15], one could presume that the comparison to these experimental results would favor one of the models suggested in Ref. [6]. ed scattering has an additional appealing characteristic, since its dependence on the πN coupling constant and on the form factor is twofold. On the one hand, it enters via the underlying NN potential and shows up, e.g., in the shape of the deuteron wave functions, the basic ingredients of the calculation. On the other hand, it has been known for a long time that a reasonable description of the scattering data of electrons on the deuteron can be achieved only by the inclusion of meson-exchange currents (MEC's). Since the most important part of them originates from pion exchange, one would expect that differences in the treatment of the πN coupling should have an influence on ed observables also via MEC's.

In the following we will show and discuss the deuteron wave functions of the OBE potentials of Ref. [6]. With these wave functions elastic *ed* and *Nd* observables were calculated. A comparison to experimental data should give the answer to the above mentioned questions on the dependence of observables on features of the πN vertex.

II. DEUTERON WAVE FUNCTIONS

Haidenbauer, Holinde, and Thomas [6] have constructed two sets of potentials, varying characteristic features of the πN vertex. The basic potential for the first set was the energy-dependent OBE potential OBEPT, which is described in [7]. For the second set the instantaneous (i.e., energy-independent) interaction model OBEPF (see Ref. [8]) was used as reference potential. The application of energy-dependent potentials in three-body calculations needs special treatment since the energy dependence has to be taken into account explicitly [16]. This provides no serious problem for the *ed* system (see, e.g., Ref. [17]), but would make things much more complicated for *Nd* scattering. Therefore we will use only the energy-independent potentials for the investigation in this paper. This is certainly no serious drawback, since, e.g., the results of Ref. [6] in the *NN* case do not show any essential difference between the two sets of potentials.

The models we use are according to the notation in Ref. [6]: OBEPF, OBEPF1, and OBEPFP. As said before, the main difference between the latter two interaction models lies in the underlying πN vertex: OBEPF1 uses a small cutoff mass (Λ_π=0.8 GeV compared to Λ_π=1.75 GeV for OBEPF and OBEPFP), whereas OBEPFP is characterized by a small coupling constant ($g_\pi^2/4\pi$=13.3 compared to $g_\pi^2/4\pi$=14.4 for OBEPF and OBEPF1). There are also some differences in other parameters (see Table II of Ref. [6]), which we will discuss in Sec. IV.

Figure 1 shows the *s*- and *d*-state wave functions of the

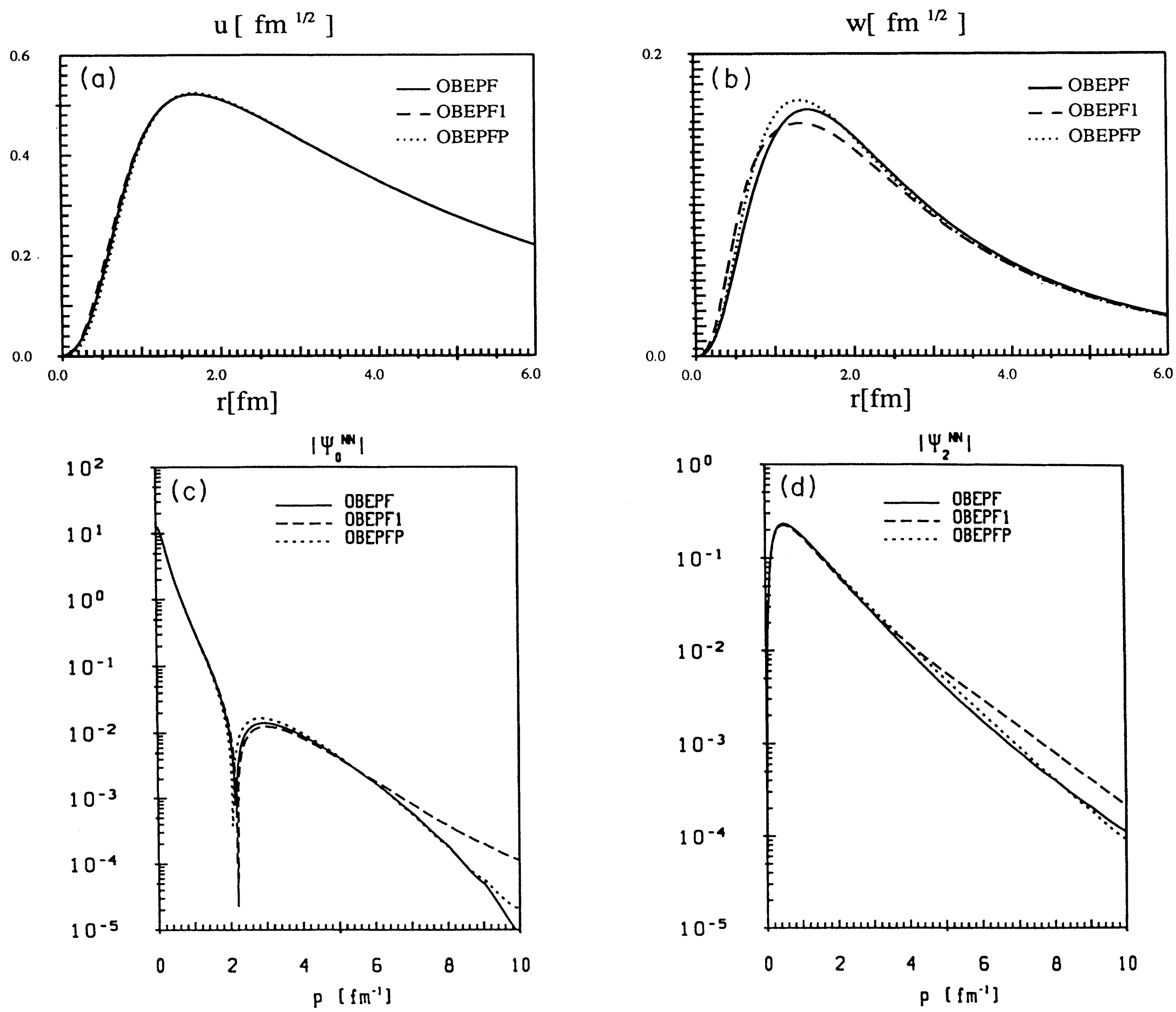

FIG. 1. Deuteron wave functions for the *s* and *d* state: (a), (b) in coordinate space; (c), (d) in momentum space. The solid line shows OBEPF; the dashed and dotted lines originate from OBEPF1 and OBEPFP.

deuteron of the three potentials, in both coordinate and momentum space. The s-state wave functions $u(r)$ do not show larger differences, whereas the corresponding $\psi_0(p)$ of OBEPF1 has larger values than the others at $p \geq 6$ fm^{-1}. $w(r)$ shows differences which are caused mainly by different d-state probabilities of the models: p_D=5.66, 5.41, and 5.86 for the potentials OBEPF, OBEPF1, and OBEPFP, respectively. By viewing the plots of $\psi_2(p)$ one would expect that OBEPF1 has a larger d-state probability than OBEPFP. But $\psi_2(p)$ falls off very fast and therefore just the momentum region $0.5 \leq p \leq 4$ fm^{-1} gives the essential contributions to p_D—in this region the d wave of OBEPFP is slightly larger.

All three d waves do not change sign in momentum space at least up to $p \approx 10$ fm^{-1}. This is in contrast to wave functions of other meson-theoretical models such as the Paris potential [18], and it also differs from the wave function of the energy-dependent Bonn potential [17,19].

This kind of difference shown in Fig. 1 is expected to become visible also in ed observables at a momentum transfer q, which is roughly given by $q \simeq 2p$ [20]. But first we will look to see if these differences are transferred to Nd observables.

III. Nd SCATTERING

Considerable progress has been made in recent years in the theoretical and numerical treatment of elastic Nd scattering, made possible not the least by the availability of larger and faster computers. In particular, it has become feasible to calculate Nd observables for modern meson-theoretical potentials such as the Paris [18] or Bonn [7] NN interactions, first via separable expansions [9] and then also directly [10]. The comparison to Nd experiments attested a fair overall concordance but, at the same time, disclosed some striking exceptions, notably the nucleon analyzing power A_y at energies $E_N \leq$ 20 MeV [10, 11]. In order to remedy this obvious shortcoming, several suggestions were brought forward, for example, the inclusion of $3N$ forces [21] or a modification of the (low-energy) NN p waves, to which the Nd analyzing power is very sensitive [11]. Since the interaction models of Haidenbauer, Holinde, and Thomas led to noticeable variations in the p waves (cf. Table V of Ref. [6]), the question arises how this affects Nd predictions. Indeed, if any of the models can reduce the deviations of the theoretical result from the data, this would provide an additional (and independent) support for either a softer πN form factor or a smaller πN coupling constant.

Our calculations were done with a momentum-space Faddeev code [22] taking into account two-nucleon subsystems up to $J \leq 2$. The code is developed for separable interactions; therefore, the potentials of Haidenbauer, Holinde, and Thomas [6] had to be cast into separable form. This was done in a straightforward way using the so-called Ernst-Shakin-Thaler method [23]. Here we followed closely the procedure outlined in Refs. [9] and [24]. Note that with separable expansions of sufficiently high rank convergence on the three-body level can be achieved [24]. Indeed, it was demonstrated in a recent work by Cornelius *et al.* [25] that results of three-body calculations using local potentials or their (converged) separable represention are essentially indistinguishable (at least in the low-energy regime with which we are concerned here).

Via the separable expansion, the relativistic OBEPF models are also transformed into nonrelativistic potentials as required by our Faddeev code. Since thereby the on- as well as (half-)off-shell properties are preserved [23], this has, however, no relevance for the present investigations. For the same reason Coulomb effects in the $3N$ system are neglected.

Figure 2 exhibits the nucleon-to-nucleon spin-transfer coefficients $K_x^{x'}$, $K_y^{y'}$, and $K_z^{x'}$, respectivley, at a nucleon

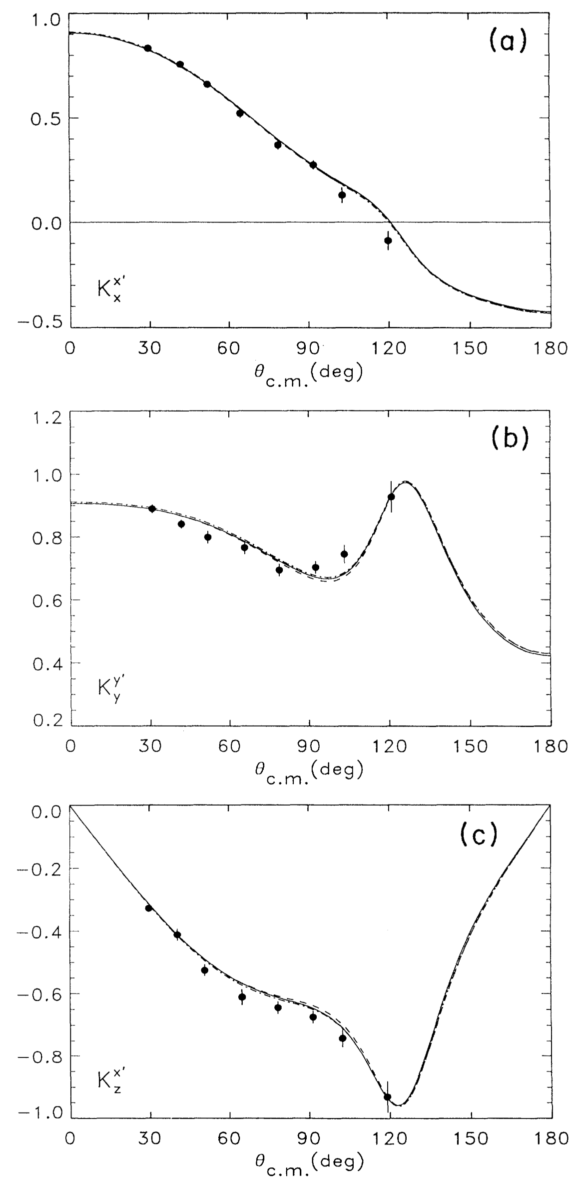

FIG. 2. Nucleon-to-nucleon spin-transfer coefficients (a) $K_x^{x'}$, (b) $K_y^{y'}$, and (c) $K_z^{x'}$ in elastic Nd scattering at a nucleon laboratory energy of 10 MeV. The experimental data are from Ref. [26]; the notation is the same as in Fig. 1.

laboratory energy of 10 MeV. One can recognize a very good agreement with the experiments of Ref. [26]. Evidently, the results for the three underlying potentials OBEPF, OBEPF1, and OBEPFP are almost identical.

The results for the analyzing powers iT_{11} and A_y are compared to the experimental data of Refs. [27] and [28] in Fig. 3, again for $E_N = 10$ MeV. All graphs show the well-known discrepancy between theory and experiment; neither the model with the soft πN form factor nor the one with a reduced coupling constant yields any significant improvement. This is to some extent surprising since Witala and Glöckle have shown that changes of the ^3p waves, in a magnitude comparable to those generated by OBEPF1 and OBEPFP, can, in fact, resolve the disagreement of theory and experiment for A_y [11]. A closer inspection of the phases gives an explanation for the "failure" of the OBEPF models. The weakening of the long-range tensor force (by either a softer πN form factor or a smaller coupling constant) leads to a smaller tensor combination Δ_T of the NN ^3p waves (cf. Table I). The same trend can be seen in the (by hand) modified phases of Witala and Glöckle. However, the variations of the ^3p waves done in Ref. [11] in order to reproduce the Nd analyzing powers imply also rather drastic changes in the spin-orbit as well as central combinations (Δ_{LS} and Δ_C, respectively) as is shown in Table I. Naturally, such

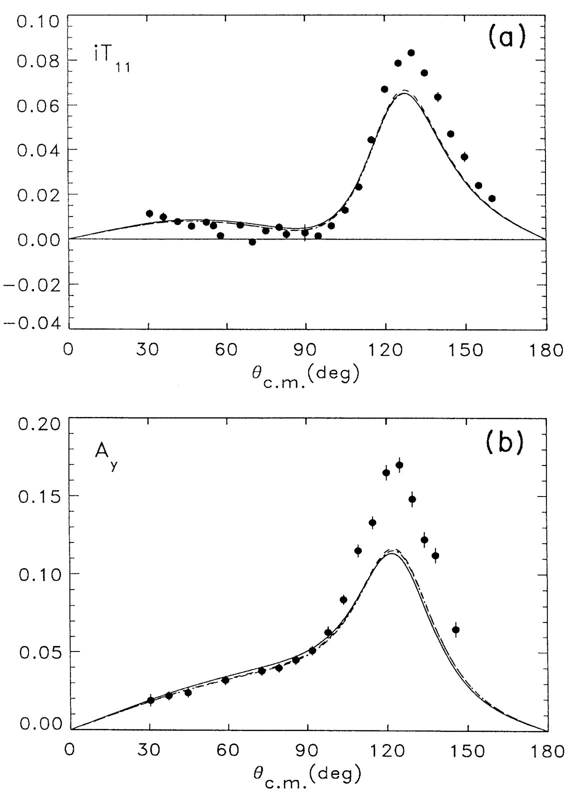

FIG. 3. (a) Deuteron vector analyzing power iT_{11} and (b) nucleon analyzing power A_y, for elastic Nd scattering at a nucleon laboratory energy of 10 MeV. The experimental data are from Refs. [27] and [28]; the notation is the same as in Fig. 1.

TABLE I. Tensor (Δ_T), spin-orbit (Δ_{LS}), and central (Δ_C) pp p-wave phase-shift combinations (in degrees) for the OBEPF-type interaction models at $E_{\mathrm{lab}} = 9.85$ MeV. The values for "Witala-Glöckle" correspond to the modified Bonn B potential of Ref. [11], while "Nijmegen" refers to their phase-shift analysis [29].

	Δ_T	Δ_{LS}	Δ_C
OBEPF	-1.023	0.109	0.047
OBEPF1	-0.991	0.119	0.039
OBEPFP	-0.950	0.122	0.046
Witala-Glöckle	-0.940	0.278	-0.023
Nijmegen	-0.935	0.206	0.075

changes cannot be accomplished by modifications of the πN vertex alone.

We have performed Nd calculations also for other observables and at somewhat higher energies; the results showed the very same insensitivity.

In conclusion, one can say that three-nucleon observables below a laboratory nucleon energy of 20 MeV do not show a dependence on the variations due to a different treatment of the pion coupling. Therefore it is very unlikely that one can gain further information on the πN vertex via investigations of the $3N$ system.

IV. ELASTIC ed SCATTERING

Three quantities are measured in elastic *ed* scattering, partly with high precision and up to large momentum transfer: the electric and magnetic form factors $A(q^2)$ [12,13] and $B(q^2)$ [14,15] and the tensor analyzing power $T_{20}(q^2)$ [30]. Therefore we will base also our discussion just on these three observables.

The calculation was performed in the usual way, i.e., starting from a nonrelativistic impulse approximation and then adding relativistic corrections (RC's) and terms due to meson-exchange currents (MEC's). As said before, variations of the pion exchange have an influence on the impulse approximation as well as on the MEC's. In the following we will discuss these two parts separately.

The expressions for $A(q^2), B(q^2)$, and $T_{20}(q^2)$ in a nonrelativistic impulse approximation are unambigous [31]. For the actual calculation some uncertainties appear which are related to the treatment of the underlying nucleons. The question whether to use Dirac or Sachs form factors is still unsettled—in our calculations Dirac form factors were applied. Another uncertainty concerns the neutron electric form factor. Because of the lack of experimental knowledge about this observable, its shape is quite unclear and there exist several parametrizations for it [32–34]. We used the parametrization of Höhler *et al.* [32] for the magnetic and electric form factors of the nucleons. The specific choice is important for the comparison of our results with experimental data; it is essentially of no relevance for the comparison of the models of Haidenbauer, Holiude, and Thomas among each other.

Figure 4 gives the results of the impulse approximation of the potentials of Ref. [6] whose wave functions are shown in Fig. 1. $A(q^2)$ is to a large extent dominated by the s wave. Since the different potentials yield very similar s-state wave functions, it is no surprise that the outcome for $A(q^2)$ is almost identical. $B(q^2)$ is much more influenced by the d wave, which results in a splitting of the results already at $q^2 > 30\ \mathrm{fm}^{-2}$. It should be noted that both changes, namely, decreasing the πN coupling constant or softening the πN form factor, act in the same direction, but that the variation of the form factor has a larger influence. This trend is even more pronounced in the tensor polarization $T_{20}(q^2)$, which gives almost identical results for OBEPF and OBEPFP, whereas OBEPF1 shows some deviation.

Since these deviations are in regions where the absolute values of the data are very small [$B(q^2)$] or where experiments are extremely difficult [$T_{20}(q^2)$], it will not be possible to discriminate this kind of differences on the basis of experimental data in the near future, especially since other uncertainties of the calculation are of the same order of magnitude, e.g., the already mentioned electric neutron form factor and contributions of meson-exchange currents, which we will discuss next.

Possible and necessary extensions of the nonrelativistic impulse approximation have been a point of long controversy, where one could classify the work into two broad categories. The first claims that a calculation is meaningful and trustworthy only when the NN potential and the coupling to the photon are treated on the same footing in a consistent manner. The other group tends to handle the problem as a kind of perturbation theory where one takes into account the largest contributions and believes to know (with more or less physics support) which the largest parts are. Attempts to be as pure as possible were made with regard to relativistic effects, e.g., by Hummel and Tjon [44], and with regard to MEC's by Buchmann,

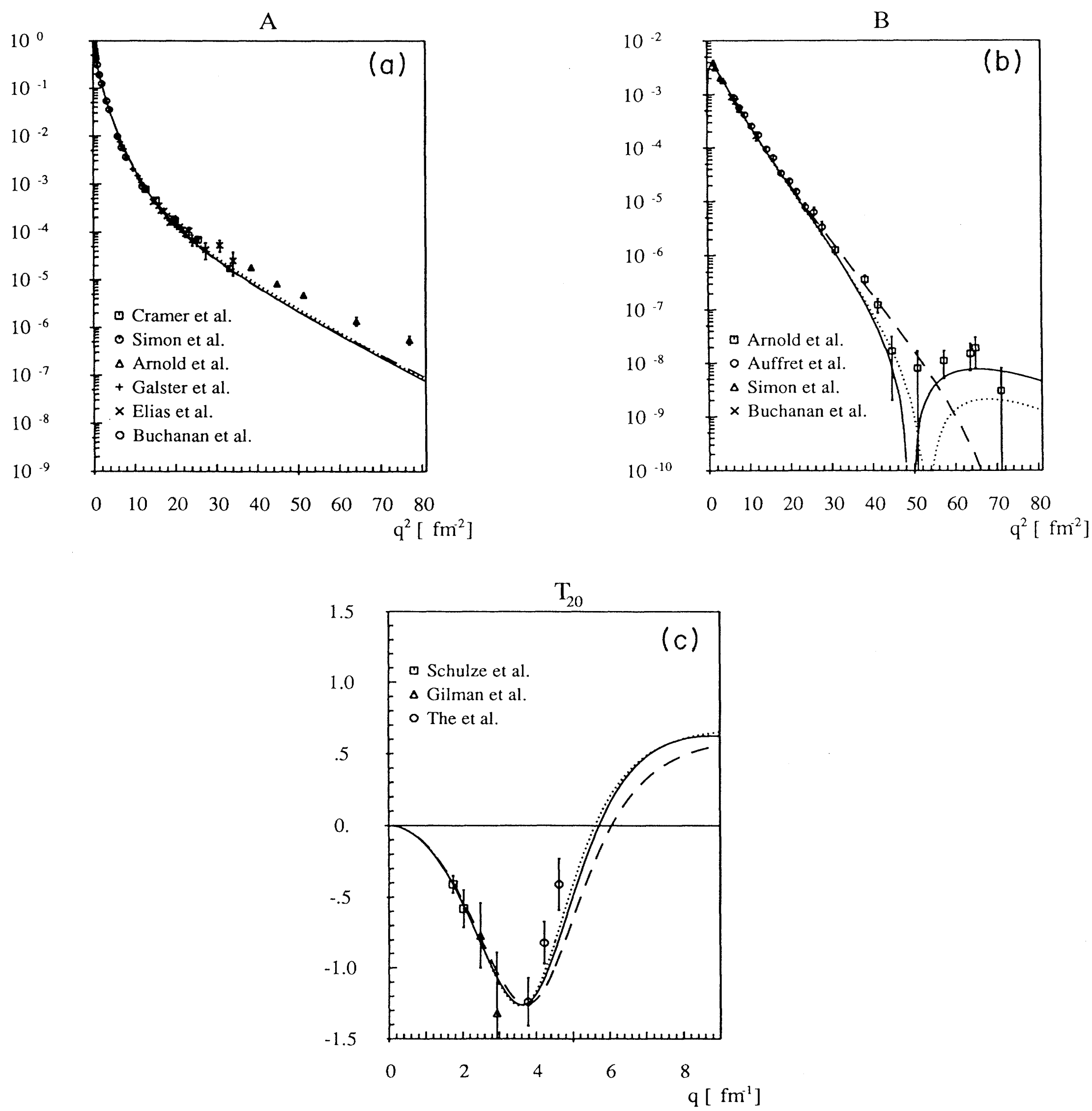

FIG. 4. Electron-deuteron observables (a) $A(q^2)$, (b) $B(q^2)$, and (c) $T_{20}(q^2)$ in the impulse approximation. The experimental data are from Refs. [12,14,30,35–43]; the notation is the same as in Fig. 1.

Leidemann, and Arenhövel [45] and Schiavilla and Riska [46].

With regard to this paper the underlying potentials are already given in a specific framework which makes a consistent relativistic treatment impossible. Therefore we include in our calculation those contributions which are expected to dominate [47]: the Darwin-Foldy term, the contribution due to the nuclear motion, and the spin-orbit contribution.

Buchmann, Leidemann, and Arenhövel [45] and Schiavilla and Riska [46] calculated MEC's for the Paris potential taking into account consistently the π and ρ exchange. In this paper we insert *ad hoc* the following MEC's: the so-called π-pair term, the π retardation, and $\rho\pi\gamma$ currents [48]. Consistency in our case means that we use exactly the same form for the πN vertex as inherent in the particular potential model, i.e., pseudoscalar coupling and corresponding coupling constants as well as (strong) form factors and cutoff masses.

Figure 5 shows the same kind of effect on all three observables (compare with Fig. 4): MEC's, in particular the pair term, produce large contributions. The magnitude of the contribution is very similar for OBEPF and OBEPFP and definitely smaller for OBEPF1, which means that the two different coupling constants produce almost the same result, whereas the variation in the cutoff mass influences the final result to a large extent. [It was shown already by Mathelitsch, Schwarz, and Zingl [49] that the size of the pion-nucleon form factor has great importance for the observable $A(q^2)$ even at small momentum transfer.] A comparison of the size of the deviation and of the error bars of the experimental data shows clearly that this kind of difference, originating from the soft πN form factor, should be measureable.

As we shall see next, one has to be careful with the last conclusion: It is true in principle, namely, regarding just the effect of different cutoff masses on *ed* observables. But one has to keep in mind that the πN form factor was

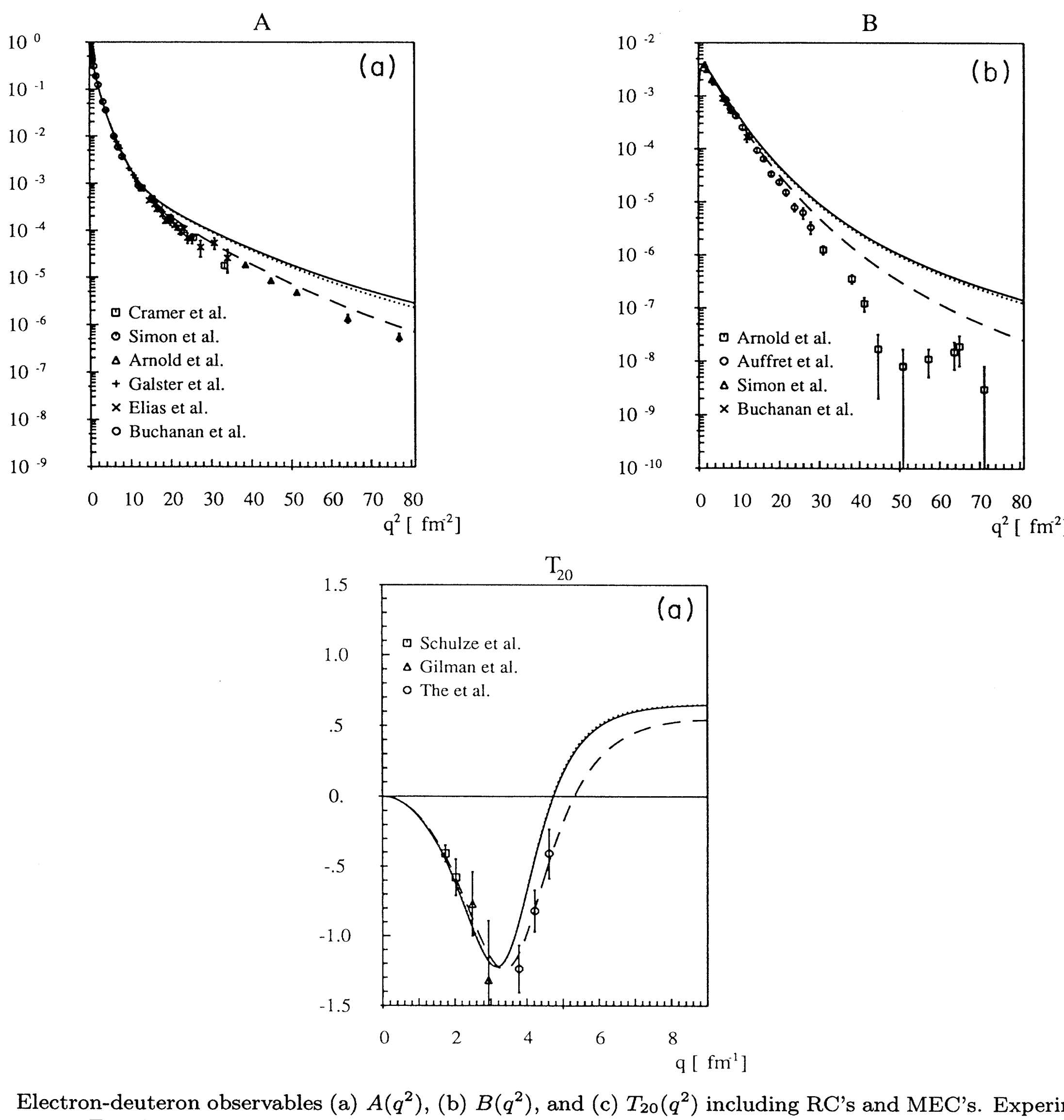

FIG. 5. Electron-deuteron observables (a) $A(q^2)$, (b) $B(q^2)$, and (c) $T_{20}(q^2)$ including RC's and MEC's. Experimental data and notation as in Fig. 4.

changed within the framework of a NN potential which is fitted to experimental data. If the cutoff mass has a similarly large influence on NN observables (as on *ed* quantities, shown before), then the reduction of the πN cutoff mass should be accompanied by variations of some other parameters of the potential in order to preserve the good fit to the data.

Table II of Haidenbauer, Holinde, and Thomas shows that OBEPF1 and OBEPFP differ in several aspects (coupling constants, cutoff masses), the most drastic change occurring with the introduction of the (short-ranged) π' meson [6, 50]. We will not repeat here the discussion about the origin and purpose of the π': Whether it is a physical particle (with more or less known mass but completely unknown coupling constant) or whether it mimics certain short-range contributions to the NN interaction such as multimeson and/or quark and gluon exchange [50, 51]. In both cases the π' is connected with free parameters which were used in Ref. [6] to reinstate the (correct) reproduction of the deuteron properties, notably the quadrupole moment. But since the π' has such an influence on the static properties of the deuteron, the question arises if a similar effect is seen also in observables of *ed* scattering. Therefore we treated the π' similarly to the π: We calculated the largest MEC, namely, the pair term, also for the π' and added this contribution to the results of Fig. 5.

As can be seen in Fig. 6, most of the splitting between OBEPFP and OBEPF1 disappears and the final results lie almost as close together as was the case already for the impulse approximation. That means that the soft πN form factor of OBEPF1 produces a relative small MEC, but in this case the π' has such a large coupling constant that it yields a MEC of roughly the same size.

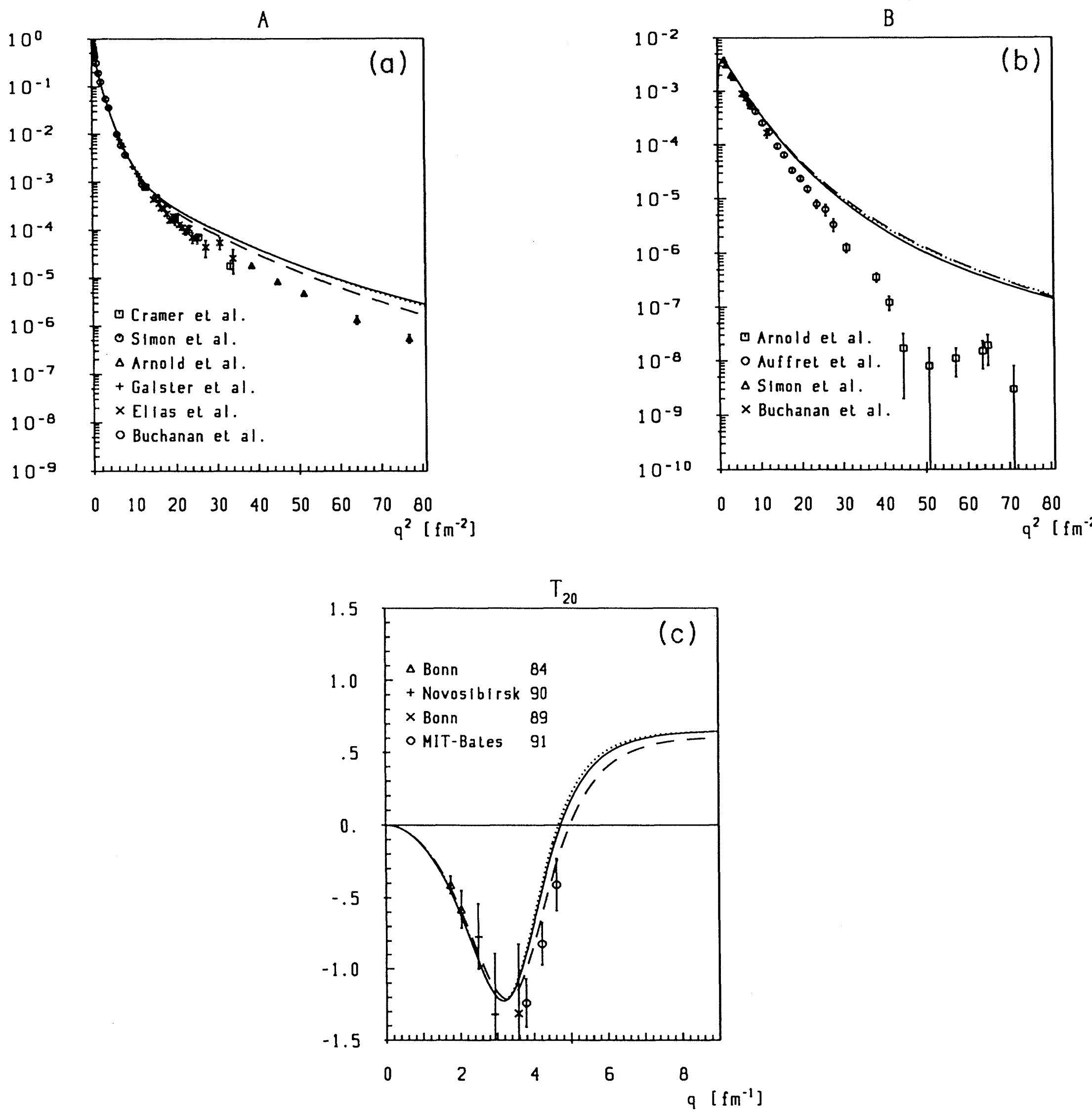

FIG. 6. Electron-deuteron observables (a) $A(q^2)$, (b) $B(q^2)$, and (c) $T_{20}(q^2)$ including RC's and MEC's (for π and π'). Experimental data and notation as in Fig. 4.

The sum of the two contributions is as large as the sum of the large contribution of the pion and the very small contribution of π' for the potential OBEPFP.

It is striking that the agreement of the final (theoretical) result (i.e., impulse approximation plus relativistic and meson-exchange corrections also for π') with the experimental data is not satisfactory for all three observables. For the electric form factor $A(q^2)$, the curves of the three potentials lie well above the experimental data for $q^2 \geq 20$ fm^{-2}. The main reason for this behavior is caused by the respective d-state wave functions which do not show a sign change up to a high momentum [see Fig. 1(d)]. Other versions of the Bonn-potential, which have a sign change around $p \approx 6$ fm^{-1}, reproduce the experimental data satisfactorily (with the same parametrizations of nucleon form factors and the same RC's and MEC's as used in this paper [19]). The reason for the disagreement in the magnetic form factor is more subtle since several ingredients (neutron electric form factor, RC's, MEC's, shape of s and d waves) play an important role.

V. CONCLUSION

Haidenbauer, Holinde, and Thomas studied in Ref. [6] the implications of either a soft πN form factor or a small coupling constant on NN and $N\bar{N}$ observables by means of a set of appropriately modified OBE potential models. The aim of this paper was to extend this study to three-body reactions where also the off-shell component of the interaction may be of relevance. But the similarity of especially the s-state wave functions of the deuteron indicates already that the three investigated models do not differ too much in the off-shell regime.

It was expected that deviations of the NN phase shifts in the p state should show up in Nd observables, especially in the nucleon analyzing power. But it turned out that all observables are to a large extent independent of the variations in the underlying two-nucleon interaction considered.

The situation is more interesting in the case of elastic electron-deuteron scattering. Although the similar wave functions of the three models result in almost indistinguishable graphs in the impulse approximation, the inclusion of MEC's (especially of the π-pair graph) yields a substantial splitting in *ed* observables. In particular, the low value of the cutoff mass leads to a deviation from the other results, which is larger than several standard deviations of the existing experimental data.

But the treatment of the "π' meson" in the same way as the π compensates the effect of the soft πN form factor almost entirely; the reason seems to be the following: Decreasing the cutoff mass (within an otherwise fixed model) changes drastically deuteron properties such as the asymptotic D/S ratio or the quadrupole moment. In order to regain these quantities, Haidenbauer, Holinde, and Thomas exploited mainly the freedom of the π'. Our investigation shows that the π' has the same influence also on *ed* observables as on the deuteron itself, namely, more or less to take over the missing part of π', so that in total the same results show up again.

Therefore one has to conclude that — at least within the ansatz of Haidenbauer, Holinde, and Thomas and at the regarded energies — it is not possible to gain additional information on the πN vertex via elastic Nd and *ed* scattering.

ACKNOWLEDGMENTS

We want to thank Professor W. Plessas and Professor K. Holinde for helpful suggestions and valuable discussions. This work was supported in part by the Australian Research Council.

[1] J.R. Bergervoet, P.C. van Campen, T.A. Rijken, and J. de Swart, Phys. Rev. Lett. **59**, 2255 (1987); J.R. Bergervoet *et al.*, Phys. Rev. C **41**, 1435 (1990); R.A.M. Klomp, V.G.J. Stokes, and J.J. de Swart, *ibid.* **44**, 1258 (1991).
[2] R.A. Arndt, Z. Li, L.D. Roper, and R.L. Workman, Phys. Rev. Lett. **65**, 157 (1990); Phys. Rev. D **44**, 289 (1991).
[3] R. Machleidt and F. Sammarruca, Phys. Rev. Lett. **66**, 564 (1991).
[4] T.E.O. Ericson, Nucl. Phys. **A453**, 409c (1992).
[5] R.G.E. Timmermans, T.A. Rijken, and J.J. de Swart, Phys. Rev. Lett. **67**, 1074 (1991).
[6] J. Haidenbauer, K. Holinde, and A.W. Thomas, Phys. Rev. C **45**, 952 (1992).
[7] R. Machleidt, K. Holinde, and Ch. Elster, Phys. Rep. **149**, 1 (1987).
[8] J. Haidenbauer, K. Holinde, and M.B. Johnson, Phys. Rev. C **45**, 2055 (1992).
[9] Y. Koike, J. Haidenbauer, and W. Plessas, Phys. Rev. C **35**, 396 (1987).
[10] W. Glöckle, H. Witala, and Th. Cornelius, Few Body Syst. Suppl. **2**, 55 (1987); Nucl. Phys. **A496**, 446 (1989); **A508**, 115c (1990).
[11] H. Witala and W. Glöckle, Nucl. Phys. **A528**, 48 (1991).
[12] R.G. Arnold *et al.*, Phys. Rev. Lett. 58, 1723 (1987).
[13] S. Platchkov *et al.*, Nucl. Phys. **A510**, 740 (1990).
[14] S. Auffret *et al.*, Phys. Rev. Lett. **54**, 649 (1985).
[15] P.E. Bosted *et al.*, Phys. Rev. C **42**, 38 (1990).
[16] J.L. Friar, in *Mesons in Nuclei*, edited by M. Rho and D. Wilkinson (North-Holland, Amsterdam, 1979), Vol. 2, p. 595.
[17] J. Pauschenwein, L. Mathelitsch, and W. Plessas, Nucl. Phys. **A508**, 253c (1990).
[18] M. Lacombe *et al.*, Phys. Rev. C **21**, 861 (1980).
[19] J. Pauschenwein, W. Plessas, and L. Mathelitsch, Few-Body Syst. Suppl. **6**, 195 (1992).
[20] L. Mathelitsch and H.F.K. Zingl, Nuovo Cimento **A44**, 81 (1978).
[21] W. Tornow *et al.*, in *The Three-Body Force in the Three-Nucleon System*, Proceedings of the International Symposium Held at the George Washington University,

Vol. 260 of *Lecture Notes in Physics*, edited by B.L. Berman and B.F. Gibson (Springer, New York, 1986), p. 251.
[22] Y. Koike and Y. Taniguchi, Few-Body Syst. **1**, 13 (1986).
[23] D.J. Ernst, C.M. Shakin, and R.M. Thaler, Phys. Rev. C **8**, 507 (1973).
[24] J. Haidenbauer and Y. Koike, Phys. Rev. C **34**, 1187 (1986).
[25] Th. Cornelius *et al.*, Phys. Rev. C **41**, 2538 (1990).
[26] F. Sperisen *et al.*, Phys. Lett. **102B**, 9 (1981).
[27] P. Doleschall *et al.*, Nucl. Phys. **A380**, 72 (1982).
[28] W. Tornow, C.R. Howell, R.C. Byrd, R.S. Pedroni, and R.L. Walter, Phys. Rev. Lett. **49**, 312 (1982).
[29] J.R. Bergervoet, P.C. van Campen, W.A. Van der Sanden, and J.J. de Swart, Phys. Rev. C **38**, 15 (1988).
[30] I. The *et al.*, Phys. Rev. Lett. **67**, 173 (1991).
[31] M.I. Haftel, L. Mathelitsch, and H.F.K. Zingl, Phys. Rev. C **22**, 1285 (1980).
[32] G. Höhler *et al.*, Nucl. Phys. **B114**, 505 (1976).
[33] E.L. Lomon, Ann. Phys. (N.Y.) **125**, 309 (1980).
[34] M. Gari and W. Krümpelmann, Z. Phys. A **322**, 698 (1985).
[35] R. Cramer *et al.*, Z. Phys. C **29**, 513 (1985).
[36] G.G. Simon *et al.*, Nucl. Phys. **A364**, 285 (1981).
[37] R.G. Arnold *et al.*, Phys. Rev. Lett. **35**, 776 (1975).
[38] S. Galster *et al.*, Nucl. Phys. **B32**, 221 (1971).
[39] J.E. Elias *et al.*, Phys. Rev. **177**, 2075 (1969).
[40] C.D. Buchanan and M.R. Yearian, Phys. Rev. Lett. **15**, 303 (1965).
[41] M.E. Schulze *et al.*, Phys. Rev. Lett. **52**, 597 (1984).
[42] V.F. Dmitriev *et al.*, Phys. Lett. **157B**, 143 (1985).
[43] R. Gilman *et al.*, Phys. Rev. Lett. **65**, 1733 (1990).
[44] E. Hummel and J.A. Tjon, Phys. Rev. C **42**, 423 (1990).
[45] A. Buchmann, W. Leidemann, and H. Arenhövel, Nucl. Phys. **A443**, 726 (1985).
[46] R. Schiavilla and D.O. Riska, Phys. Rev. C **43**, 437 (1991).
[47] J. Friar, Ann. Phys. (N.Y.) **81**, 332 (1973).
[48] M. Gari and H. Hyuga, Nucl. Phys. **A264**, 409 (1976).
[49] L. Mathelitsch, K. Schwarz, and H.F.K. Zingl, Czech. J. Phys. B **36**, 305 (1986).
[50] K. Holinde and A.W. Thomas, Phys. Rev. C **42**, 1195 (1990).
[51] T. Ueda, Phys. Rev. Lett. **68**, 142 (1992).