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One-boson-exchange potential based on a soft pion form factor

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A new one-boson-exchange potential is presented in which the pion-nucleon form factor is taken to be much softer than usual. The fit to N-N phase shifts and deuteron properties is quantitatively as good as for recent potentials of more conventional form, such as OBEPT (a former version of the Bonn potential). As anticipated in earlier work the tensor combination of P-wave phase shifts, Δ_T, is somewhat reduced for the new potential in comparison with the original.

For the past thirty years one-boson-exchange (OBE) models have provided a physically well-motivated and convenient microscopic parametrization of the nucleon-nucleon (N-N) force.[1–5] Beginning with the lightest meson, namely the pion, and moving up in mass one aims to build a picture of the interaction at smaller N-N separation. The short-range repulsion by ω exchange means that one should not be so sensitive to the necessary truncation in the spectrum of exchanged mesons. The parameters of an OBE model are the meson masses, coupling constants, and the form factors at the meson-nucleon vertices. Conventionally, these form factors, which act to cut off the meson-exchange force at short distance, are taken to have a monopole form with a mass parameter Λ_α larger than the heaviest exchanged meson. Typically, one uses values for λ_α in the range of 1.3–1.5 GeV.

Since this sort of model is intended to provide a microscopically correct representation of the N-N interaction, the parameters should be constrained, as far as possible, by independent data. Only when this is not possible should they be treated as fitting parameters. In this respect it is perhaps surprising that pion exchange has proven most controversial.[6–8] In the past the mass parameter (Λ_π) in the (monopole) form factor at the πNN vertex has typically been fixed at 1.3 GeV or higher. This was usually done on the grounds that it was difficult to obtain a realistic tensor force (including the properties of the deuteron) if Λ_π was made smaller. On the other hand, there is now a considerable body of evidence suggesting that the form factor associated with the emission of an off-mass-shell pion from a single nucleon (which is the quantity needed for the long-range N-N force) is quite soft. In a recent paper[6] we suggested that the evidence was strongly in favor of a cutoff mass (for a monopole form) Λ_π around 730 MeV—with a conservative error of ± 100 MeV. Moreover, we suggested that such a soft form factor could provide a natural explanation of the anomalously large apparent charge dependence of the πNN coupling constant extracted from an analysis of pp scattering data by the Nijmegen group.[9,10]

At that time we made it clear that it remained to be seen whether a realistic description of the N-N force could be obtained using such a soft form factor. Here we present the successful results of our search for such a potential. We make no claim that the new OBE potentials reported here are unique. Nor do we yet know whether they have different consequences in other contexts in nuclear physics. However, we do know that one of them (OBEPT1) produces a description of the N-N data which is of comparable quality to the usual OBE potentials. In this case we actually compare with OBEPT (Table 8 of Ref. 5) from which OBEPT1 was evolved.

Before presenting these (n-p) potentials and showing their phase shifts and deuteron properties, it may be helpful to explain the motivation behind their construction. As just explained, we began with a soft πNN form factor. It was further assumed that this was the result of the nucleon itself being an extended object (like a bag or soliton). Some (admittedly crude) quark model calculations have suggested that quark exchange, with pion or gluon exchange, may tend to compensate, in the region where the two nucleons overlap, for the loss of tensor strength caused by the soft πNN form factor.[11,12] We therefore introduced a heavy pionlike object (the π'), with large mass (1.2 GeV here). [As this is meant to simulate complicated, short-distance physics we did not feel obliged to fix the mass at precisely the 1.3 GeV of the observed $\pi(1300)$.] It also seemed quite reasonable that other form factors might be softer than one usually assumes, and in practice we allowed Λ_ρ to vary.

In Table I we give the resulting parameter values for a fit called OBEPT1. It differs from OBEPT in three crucial ways: (i) Λ_π is set at 800 MeV; (ii) we include a π' with mass 1.2 GeV; (iii) Λ_ρ is 1.3 GeV, indeed somewhat

TABLE I. Parameters for the potential OBEPT1 (and OBEPT2 where it differs).

Mesons	$I(J^P)$	Mass (GeV)	Λ_α (GeV)	$g_\alpha^2/4\pi$	f_α/g_α
π	$1(0^-)$	0.138	0.8	14.6	···
π'	$1(0^-)$	1.2	2.0	100	···
η	$0(0^-)$	0.549	1.5	5.0	···
ρ	$1(1^-)$	0.769 (0.700)	1.3 (1.2)	0.92	6.6
ω	$0(1^-)$	0.783	1.5	20.0	···
δ	$1(0^+)$	0.983	2.0	2.881 (2.764)	···
σ	$0(0^+)$	0.55	2.0	8.383 (8.496)	···

lower than 1.5 GeV used in OBEPT. The corresponding low energy and deuteron parameters are given in Table II. Figure 1 illustrates, for low ($J=0,1,2$) phase shifts, the quality of the fit obtained, in comparison to the empirical analysis.[13] To demonstrate the sort of changes involved we also show the effect of first setting $\Lambda_\pi=0.8$ GeV in OBEPT (dotted curve).

In order to investigate whether a still lower value of Λ_ρ also works, we made a second fit in which we fixed Λ_ρ to 1.2 GeV. (An even lower value was not possible). In order to obtain reasonable results we then had to lower the ρ mass to 700 MeV (which is in fact physically motivated due to the long-range tail of isovector pion pairs exchanged between two nucleons). We then slightly readjusted the scalar meson parameters and obtained the results labeled OBEPT2 in the tables and figures.

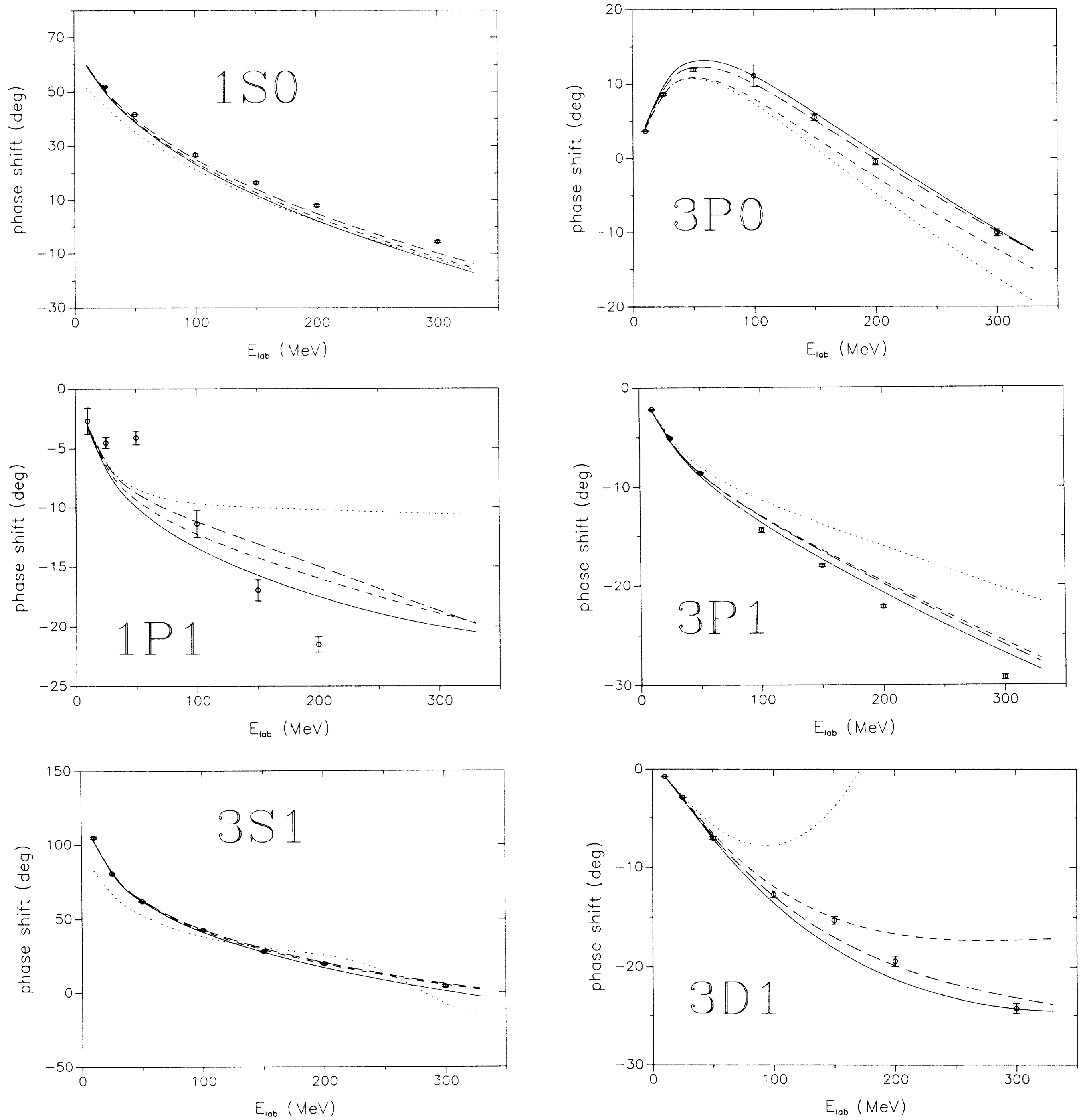

FIG. 1. Selected phase shifts for n-p scattering. The solid curve is OBEPT (Table 8 of Ref. 5). The dotted line results when setting $\Lambda_\pi=0.8$ GeV in OBEPT. The long- (short-) dashed curve is obtained when adding π' to the dotted curve and readjusting some parameters, which leads to OBEPT1 (OBEPT2). The experimental error bars are from Ref. 13.

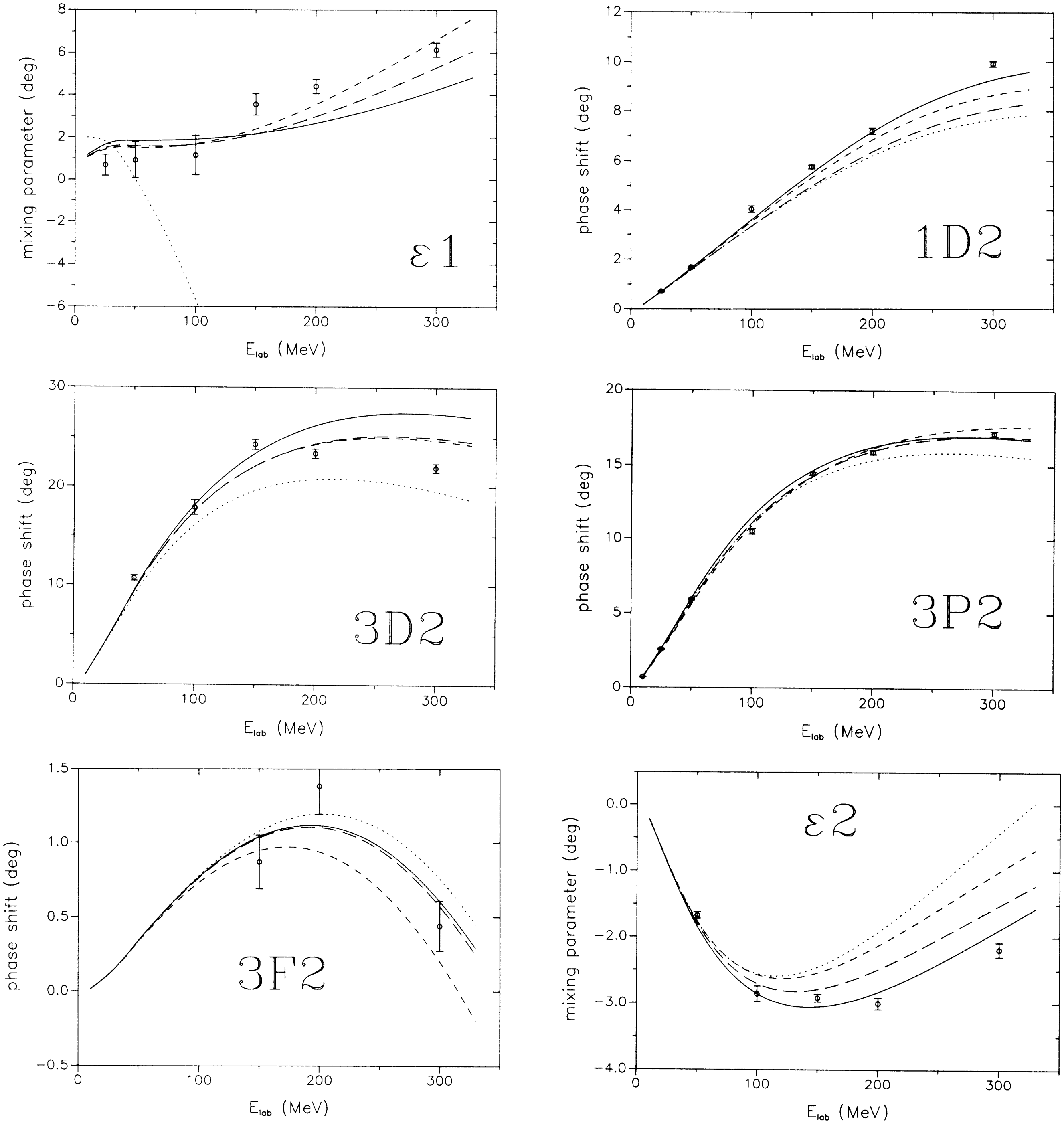

FIG. 1. Continued.

TABLE II. Low energy parameters and deuteron properties.

Potential	E_D (MeV)	Q (fm^2)	P_D (%)	a_s (np) (fm)	a_t (fm)	η
OBEPT	2.225	0.278	4.27	−23.75	5.43	0.0267
OBEPT1	2.225	0.275	4.73	−23.74	5.41	0.0262
OBEPT2	2.225	0.270	4.36	−23.73	5.43	0.0257
Data:	2.224575	0.2860	· · ·	−23.748	5.424	0.0256
	±0.000009	±0.0015		±0.010	±0.004	±0.0004

TABLE III. Scalar parameters for the p-p models, together with the $^1S_0$ p-p scattering length (in fm) and the triplet P-wave tensor combination Δ_T (in degrees).

	$g_\sigma^2/4\pi$	$g_\delta^2/4\pi$	$a_s(pp)$	Δ_T
OBEPT′	8.751	1.1585	−7.82	−1.029
OBEPT1′	8.310	2.752	−7.82	−1.004
OBEPT2′	8.417	2.624	−7.82	−0.976

As we mentioned earlier the potential OBEPT1 provides as good a fit to the N-N data as the original OBEPT. To be specific it actually fits better in $^1S_0$, $^3P_0$, $^3D_{1,2}$, and ϵ_1, while it is a little worse in $^1P_1$, $^3P_1$, $^1D_2$, and ϵ_2. It is particularly important that the deuteron properties, with their sensitivity to the tensor force, like Q and η (or A_D/A_S) are as good as for OBEPT. For comparison we observe that OBEPT2 does not give such a good overall fit to the N-N data as either OBEPT or OBEPT1.

The tensor combination of (triplet) P-wave phase shifts, Δ_T, proved to be of particular relevance in the Nijmegen work.[9] Since it is extracted from precise p-p data at low energies, a meaningful comparison requires that we start from a p-p potential, which includes the Coulomb force and predicts, after a slight readjustment of scalar coupling constants, the empirical $^1S_0$ p-p scattering length. Table III shows the modified coupling values for the corresponding p-p versions (OBEPT′, OBEPT1′, OBEPT2′), the resulting $^1S_0$ scattering length and Δ_T at $E_{\text{lab}}=9.85$ MeV. (We mention that a calculation of Δ_T with the n-p potentials presented before would yield a value about 10% larger.) As expected, the use of $\Lambda_\pi=0.8$ GeV leads to a reduction of Δ_T by about 3% (OBEPT1′) and 6% (OBEPT2′). This effect is smaller than anticipated in our earlier work,[6] mainly because part of the effect arising from the reduction of Λ_π is canceled by the introduction of the additional (short-ranged) π' contribution, which proved necessary in order to obtain a good description of the data at all energies (below pion threshold). However, the value for OBEPT1′ is not very far from the latest value reported by Bergervoet *et al.*,[10] namely an apparent reduction of $5.1\pm1.7\%$ in the value of $f^2_{\pi^0 pp}$ compared with $f^2_{\pi^+ np}$. In fact, the corresponding reduction for OBEPT2′ lies well in this range; this is our prime reason for reporting it although it does not give such a good overall fit to the N-N data as either OBEPT or OBEPT1. (Note, however, that OBEPT2 yields a slightly better ϵ_1 than OBEPT1, which is in turn better than OBEPT.)

The need for a reduction of Δ_T has been mainly deduced from empirical analyzing power data at $E_{\text{lab}}=9.85$ MeV.[14] Indeed, Fig. 2 shows that OBEPT1′ and even more OBEPT2′ are in better agreement with the data, especially around the minimum, than OBEPT′.

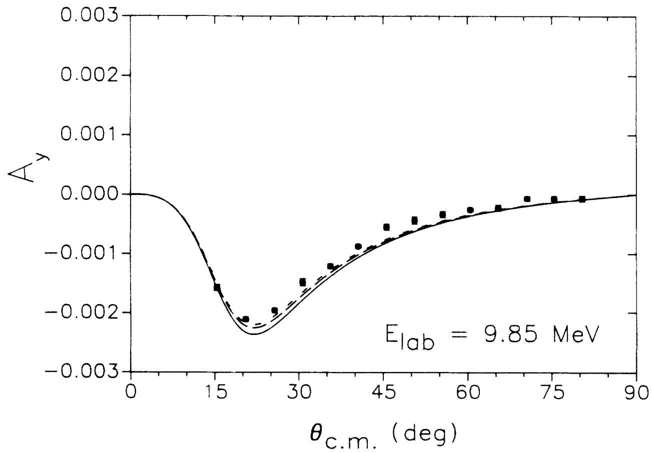

FIG. 2. p-p analyzing power at $E_{\text{lab}}=9.85$ MeV. The solid curve is OBEPT, whereas the long- (short-) dashed lines originate from OBEPT1 (OBEPT2). The experiments are from Ref. 14.

In summary, contrary to a commonly held belief, it is possible to obtain an OBE potential with a soft πNN form factor ($\Lambda_\pi=0.8$ GeV) which provides a fit to N-N data which is of the same quality as those more conventional OBE potentials widely in use. That is, the N-N data do not rule out such a form factor. The resulting potential has a softer ρ form factor, and it is also necessary to include some additional, short-range tensor force through the π'. As suggested in our earlier work, the new potential does tend to reduce the P-wave tensor combination Δ_T.

Amongst the work which needs to follow from this study we mention just three examples. First one would like to examine models of the short-distance N-N force based on composite models of nucleon structure to see whether they produce an interaction like the phenomenological π' exchange used here. Second, there is a need to include real two-pion exchange rather than the simpler scalar meson exchange used here. Third, it would be nice to see this model used in systems of more than two nucleons, to see whether the new potentials lead to any results qualitatively different from previous OBE potentials with a hard πNN for factor.

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