Nuclear Forces and Quark Degrees of Freedom

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We study the effects of quark degrees of freedom on the nucleon-nucleon observables. The model we consider is built from the Paris potential for large and intermediate distances, supplemented by the quark cluster model for the core. The fit to the existing *pp* data set is not good. These results suggest that the good description of the *NN* interaction at short distances by quark models sometimes claimed in the literature could be questioned.

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During the last three decades, a rich body of *very accurate* experimental nucleon-nucleon scattering data have been accumulated. These data can be described with great success by theoretical models based on hadron (nucleons, mesons, isobars) degrees of freedom. On the other hand, QCD is widely accepted as the underlying theory of strong interactions so that one is entitled to demand that the *NN* forces be derived directly from the quark and gluon degrees of freedom.

Attempts to tackle *quantitatively* this question have been made so far in the framework of the nonrelativistic quark-cluster model (QCM) [1]. The *NN* potential or phase shifts are derived from the quark-quark interaction; the latter is assumed to be given by a confining potential plus the one-gluon-exchange potential. The justification and reliability of such a model are based on the remarkable successes in describing the static properties of single hadrons.

In the earlier calculations [1], the *NN* *S*-wave phase shifts obtained with the QCM show that the model produces repulsive *NN* forces at short distances, which constitutes a success for the model, but fails to provide the intermediate-range attraction indispensable for binding nucleons in nuclei. This drawback is amended within the context of these models, at the expense of introducing by hand intermediate-range attraction through meson-exchange potentials between quarks or/and between nucleons (quark clusters). This procedure improves the results for the phase shifts and it is often concluded that the QCM provides a good description of the short-range (SR) part of the *NN* potential. In our opinion, however, the above procedure does not provide a rigorous test of the validity of the quark-cluster model. In order to get a clear-cut conclusion one should consider the QCM in association with an accurate and well founded model for the long- and medium-range (LR+MR) forces.

In the work reported in this Letter, we study a *NN* interaction model which satisfies this requirement. In this model, the LR+MR parts are given by the Paris *NN* potential and the SR part by the QCM. The quality of the model is then tested by confronting directly its predictions with data on observables rather than, as it is usually done, with phase shifts. We keep on emphasizing this point since we believe that phase shifts do not provide a severe enough test for theoretical models.

The model.— The interaction considered here consists of the Paris potential for the outer part and an equivalent potential between two clusters (of three quarks), given by the Hamiltonian kernel of the resonating-group method (RGM), for the inner part. For the two-nucleon system this leads to the equation

$$-\frac{1}{m}\nabla^2\psi(\mathbf{r})+V_P(E,\mathbf{r})[1-f(r)]\psi(\mathbf{r})+\int d\mathbf{r}'\,V_{\mathrm{QCM}}(\mathbf{r},\mathbf{r}')[f(r)f(r')]^{1/2}\psi(\mathbf{r}')=E\psi(\mathbf{r})\,.$$

$V_P(E,\mathbf{r})$ is the LR+MR part of the Paris potential given by the one-pion-exchange and the uncorrelated and correlated two-pion-exchange contributions [2]. This potential is local but energy dependent. $V_{\mathrm{QCM}}(\mathbf{r},\mathbf{r}')$ is the quark confinement plus the one-gluon-exchange contributions to the RGM transformed Hamiltonian kernel. This potential is taken from the recent work of Takeuchi *et al.* [3]. It contains a local and a nonlocal part. $f(r)=1/[1+(r/r_c)^{10}]$ is a cutoff function designed to make a clear separation between the SR and LR+MR parts of the interaction.

Results and discussion.— We have solved this Schrödinger equation and computed all the observables for *pp* scattering at energies below the pion production threshold. For a best fit of the data, the only free parameter r_c is adjusted to reproduce the $^1S_0$ phase shift at low energy (25 MeV). This yields $r_c=0.83$ fm. Interestingly enough, this value is very close to that used in the Paris potential to delimit the phenomenological and theoretical parts. The results are then compared with the existing world data set. The agreement with experiment is not

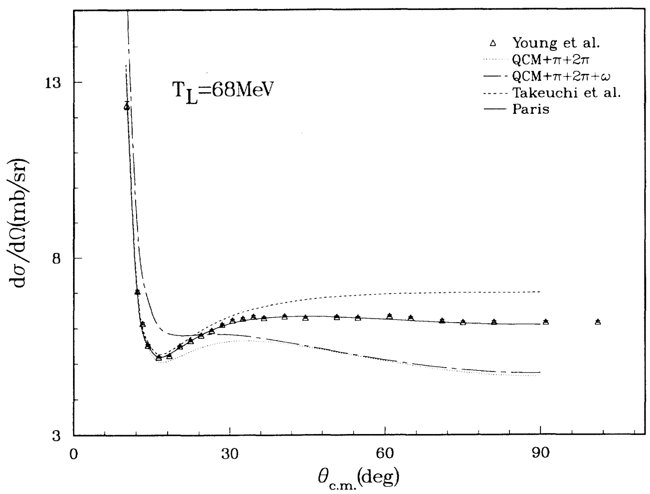

FIG. 1. *pp* elastic differential cross section at $T_L = 68$ MeV. QCM$+\pi+2\pi$ represents the model discussed in the text, and QCM$+\pi+2\pi+\omega$ the same model but with the ω exchange included. For the curve labeled Takeuchi *et al.*, see the text. Paris refers to results of Ref. [4]. The data are from Ref. [6].

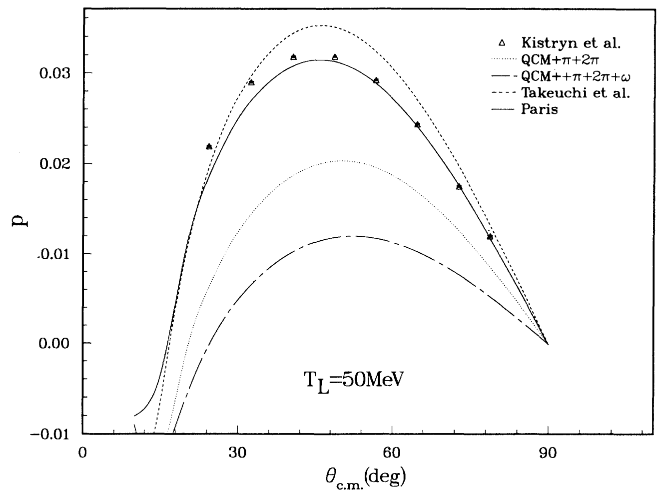

FIG. 3. *pp* elastic polarization at $T_L = 50$ MeV. Labels for the curves are the same as in Fig. 1. The data are from Ref. [8].

good, leading to a total χ^2 divided by the number of data points, χ^2/data$=100$, for 1430 data points in the range $25 < T_L < 330$ MeV. For comparison, let us recall that the Paris potential [4] gives χ^2/data$=2.4$ for the same set of data. Some typical examples of the results are displayed in Figs. 1-4. One can see that the model fails to reproduce not only the polarization but even the cross sections. Figure 4 gives an idea on the variation of the fit with energy.

Our results could seem surprising in view of conclusions which can be found in the literature. However, most of the calculations on which these conclusions are based concern only the *NN S*-wave phase shifts, apart from the works of Yamauchi *et al.* [5] and Takeuchi *et al.* [3] where other higher partial waves are also computed. Furthermore, in these calculations, phenomenological LR+MR forces, often unrealistic, are added to the QCM contribution and adjusted to get a good fit to the phase shifts. For example, in the recent and most complete work of Ref. [3], the QCM part is the same as that used in our work but the good fit to the phase shifts, in particular for the $^3P_2$ state, is obtained there at the expense of introducing a phenomenological potential with a strong attraction (which amounts to as much as 150-190 MeV

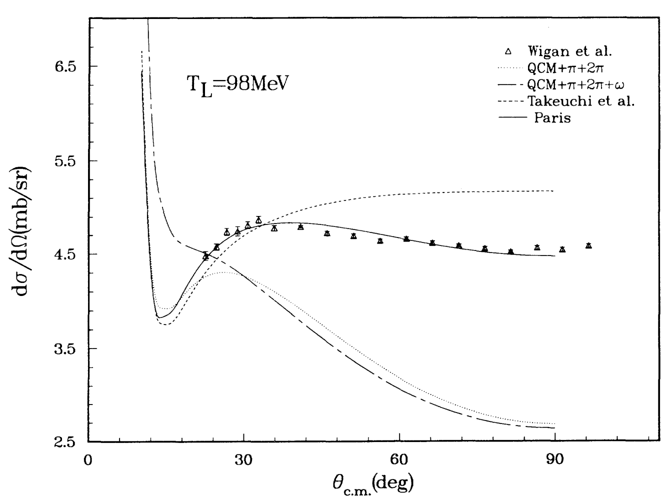

FIG. 2. *pp* elastic differential cross section at $T_L = 98$ MeV. Labels for the curves are the same as in Fig. 1. The data are from Ref. [7].

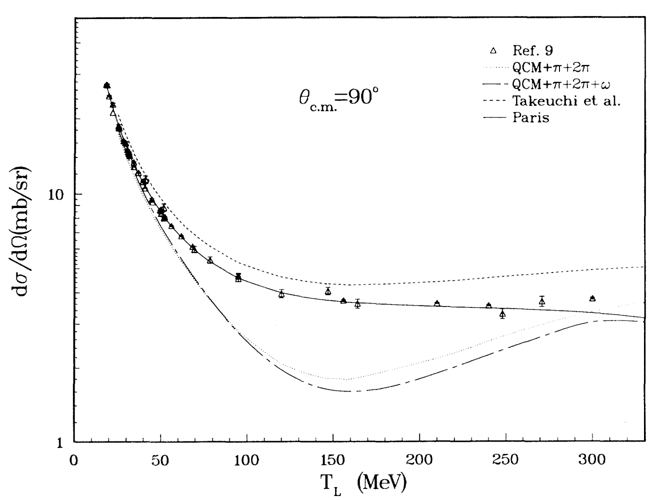

FIG. 4. *pp* elastic differential cross section at 90° vs T_L. Labels for the curves are the same as in Fig. 1. The data are from Ref. [9].

at 1 fm). For a further test of the goodness of this fit, we have made the comparison between theory and experiment at the level of observables and found a χ^2/data = 20 for the above data set. Even though this corresponds to a much better fit than that with our model, the improvement is due to a kind of compensation effect between the QCM and this strong medium-range attraction. Some results (referred to as Takeuchi *et al.*) are also shown in the figures. As can be seen, the comparison with data is still unsatisfactory.

It is worthwhile to note that the previous results are obtained without including the ω-meson-exchange potential. When this latter contribution is taken into account, even with a minimal value for the coupling constant, $g^2_{\omega NN}/4\pi = 5$, the χ^2/data increases from 100 to 160. This is due to a very large overall repulsion, indicating that the SR repulsion due to the QCM, the good feature of the model, is possibly too strong.

The quality of the fits with all the models discussed above can be judged from the figures. We have presented here only the results on *pp* scattering; those on *np* scattering show very similar features and will be reported elsewhere.

In summary, we have made a careful and detailed analysis of the quark degrees of freedom effects on the *NN* observables in the framework of the QCM. This work shows that conclusions on the ability of the QCM to describe the SR nucleon-nucleon forces clearly differ, depending on whether one adopts the viewpoint of supplementing the QCM with adjustable LR+MR forces or one chooses to associate the QCM with realistic and well founded LR+MR forces.

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