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THE S-MATRIX THEORY OF NUCLEAR FORCES

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The S-matrix theory of nuclear forces

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Abstract

The use of the S-matrix theory for deriving the nucleon-nucleon interaction is reviewed. Fits to recent NN data are described. Applications to nuclear structure properties and nucleon-nucleus reactions are also discussed, and the results compared with data.

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Introduction

Many of us certainly remember the great excitement aroused by the S-matrix theory in the early 60's. We also remember the prominent role played by Professor Chew in the development of this theory, and it seems to me appropriate at the celebration of Professor Chew's Jubilee to recall some of the successes of the S-matrix theory. Nowadays, there is a tendency to regard as obsolete the concepts, such as analyticity, unitarity and crossing symmetry attached to this theory. I hope that this talk will provide some support in their favor.

I chose, for this purpose, the illustrative example of the theory of nuclear forces. I believe this example to be relevant because

i) nuclear forces are central to physics

ii) the field of nuclear forces is the one where theory can be severely tested by experiment. We will see that several thousand nucleon-nucleon scattering data, most of them of very high accuracy, have been accumulated during the last decade. This vast wealth of data provides a very difficult test which, if it is passed successfully, would warrant to any theoretical model the correctness of its physical content.

1 - General properties of the nucleon-nucleon interaction

We now believe that nucleons and, more generally, hadrons, are made up of subhadronic constituents (quarks, gluons, etc...). One is, therefore, entitled to demand that the whole theory of nuclear forces should be derived from the degrees of freedom of those fundamental constituents. The problem in its full generality is however very difficult to carry out with accuracy and present attempts in this direction¹⁾ lead to still inconclusive results. On the other hand, simple arguments based on the confinement of quarks and

gluons can provide us some guidance for the approximations to be adopted²⁾ : Consider a system of two nucleons. When they are far apart, i.e., for internucleon distances r larger than some value of r_0 , they can only exchange colorless objects, namely *mesons*, since quarks and gluons must be confined. In the process of these exchanges, the nucleons can also find themselves, during part of the time, in excited states, namely *isobars*. On the contrary, when the overlap of the nucleons is significant, i.e., for small separation distances ($r \lesssim r_0$), the various subhadronic constituents can interact with each other and contribute to the nuclear interaction energy. The dividing line between the two phases depends of course on the size of the confinement domain. A realistic estimate for the value of r_0 gives $0.5 \text{ fm} \lesssim r_0 \lesssim 1 \text{ fm}$.

From the previous simple arguments, a reasonable approach²⁾ to the problem of nuclear forces can be based on the breaking of the interaction into two parts :

i) the long range (LR) and medium range (MR) part ($r \gtrsim r_0$), where the *meson* and *isobar* degrees of freedom are expected to provide a good approximation. In this part, consideration of quark degrees of freedom is probably unnecessary, uneconomical, and in any case does not yield reliable results at the present stage.

ii) the short range (SR) part ($r \lesssim r_0$) where the subhadronic (quarks, gluons, etc...) degrees of freedom can play, in principle, a significant role. However, their contribution can be made meaningful only through a proper account of the quark and gluon dynamics. This latter point is still unresolved.

Following the above line of reasoning, the LR part of the NN interaction is given by the exchange of one pion (OPE), since the pion is the lightest meson. The one pion exchange potential (OPEP) is well established and every theoretical NN potential contains it. The next lightest system that can be ex-

changed between the nucleons is the two pion system. Consequently, the two pion exchange (TPE) must be considered in the MR part. The exchanged pions in the TPE can be uncorrelated (Fig. 1b) or strongly correlated (Fig. 1c), since the $\pi\pi$ interaction is known to be very strong. Multipion exchanges give rise to shorter and shorter range contributions.

Fig. 1

The S-matrix theory provides a natural framework for the calculation of these particle exchange contributions to the NN interaction. Only very general properties of the S matrix, such as unitarity conditions crossing relations and dispersion relations³⁾ are needed.

2 - The Paris NN potential⁴⁾

This potential is representative of the philosophy described above. This means :

i) the (LR + MR) parts ($r \gtrsim 0.8$ fm) are given by the OPE, the TPE and the ω meson exchange, as part of the three pion exchange. The TPE is calculated carefully via dispersion relations and unitarity from the πN amplitudes and the dominant S and P waves of the $\pi\pi$ interaction. The inputs of the calculation are, thus, the πN phase shift $\delta_{\ell}^{\pi N}$ and the $\pi\pi$ phase shifts $\delta_0^{\pi\pi}$ and $\delta_1^{\pi\pi}$. The values of $\delta_{\ell}^{\pi N}$ are taken from phase shift analyses, and $\delta_0^{\pi\pi}$ and $\delta_1^{\pi\pi}$ directly from experiments. In doing so, one includes automatically all the πN isobars and the $\pi\pi$ resonances in the S wave (the ϵ meson) and in the P

wave (the ρ meson) as well as the πN and $\pi\pi$ non resonant backgrounds. In this way the uncorrelated and correlated two pion exchange is completely fixed. The coupling constant of the ω to the nucleons can be varied, although its value can, in principle, be derived from SU(6). The interested reader can find the details of these rather complicate calculations in reference (4).

ii) as mentioned above, the presently available theoretical results on the (SR) forces are still uncertain. On the other hand, there exists a rich body of experimental data. For $T_{\text{Lab}} \leq 350$ MeV, several thousand data points have been accumulated⁵⁾. For these reasons, we provisionally take a phenomenological viewpoint for the description of the (SR) part ($r \lesssim 0.8$ fm). An immediate question to the whole project arises : is this description of the actual (LR + MR) forces realistic ? This question can be answered by comparing the high partial wave phase shifts (F, G, H waves) with the empirical ones. This comparison was done in reference (6) and the agreement with experiment is satisfactory. An even better way to check the validity of the (LR + MR) forces of the Paris potential is to compare the predictions with data for observables that are sensitive to these forces. This is the case for very low energy analyzing powers or polarizations, since at very low energies the S wave is accurately known from the effective range formula, and the P and higher waves are only sensitive to the (LR + MR) forces. High precision analyzing power and polarization measurements, both in pp and np scattering, have been performed recently⁷⁾. A comparison with these data of the predictions obtained with the (LR + MR) part of the Paris potential is shown in Fig. 2.

Fig. 2a The analyzing power in pp scattering. The solid lines refer to the Paris potential predictions. The dashed lines to phase shift analysis⁸⁾. Experimental data are from reference (7).

Fig. 2b The np polarization. Experimental data are from reference (7).

Concerning the SR part, it was proposed⁹⁾ as a first step, to describe the core with a very simple phenomenological model : namely, the LR + MR ($\pi + 2\pi + \omega$) exchange potential is cut off rather sharply at an internucleon distances $r \approx 0.8$ fm and the SR ($r \lesssim 0.8$ fm) is described simply by a constant soft core. This introduces a *minimum* number (five) of adjustable parameters corresponding to the five components (central, spin-spin, tensor, spin-orbit, and quadratic spin-orbit) of the potential for each isospin state.

On the other hand, it was found that the central component of the theoretical LR + MR potential has a weak but significant energy dependence and this energy dependence is, in a very good approximation, linear. One then expects also an energy dependence in the SR part. Indeed, fitting the data required an energy dependent core for the central potential, the energy dependence being again linear. This introduces one additional parameter, the slope of the energy dependence. The proposed SR part is then determined by fitting all the known phase shifts ($J \leq 6$) up to 330 MeV and the deuteron parameters. Although the number of free parameters is small (six in total for each isospin state) the quality of the fit is very good⁹). The χ^2/data are as good as the ones given by the best phenomenological potentials, which contain many more free parameters :

$$\chi^2/\text{data} = \begin{cases} 2.5 \text{ for pp scattering} \\ 3.7 \text{ for np scattering} \end{cases} \text{ with the Paris potential}$$

$$\chi^2/\text{data} = 2.4 \text{ for pp + np scattering with the Reid soft core potential.}$$

Examples of the fit are shown in Table 1 and Fig. 3.

E_D	Q_D	$P_D\%$	μ_D
-2.2246	.290	6.75	.8392
$(-2.2246 \pm .001)$	$(.2875 \pm .002)$		$(.8574 \pm .000006)$
a_{np}	r_{np}	a_{pp}	r_{pp}
5.4179	1.753	-7.817	2.747
$(5.413 \pm .005)$	$(1.748 \pm .005)$	$(-7.823 \pm .01)$	$(2.794 \pm .015)$

The deuteron and effective range parameters. Experimental results are given in brackets.

Table 1

Fig. 3 Comparison of the phase shifts calculated from the Paris potential with the experimental results of reference (8)

The previous model was purposely chosen in its simplest form to demonstrate that, once the (LR + MR) forces are accurately determined, the (SR) forces can be described by a model with few parameters that does not affect the (LR + MR) part. This simple model, in which a definite separation between the theoretical and phenomenological parts is made, is designed to provide a clear physical insight into the problem. However, the explicit expression of the resulting potential is not very convenient for practical use in many-body calculations.

In a subsequent paper¹⁰⁾, an analytical expression for the *complete* potential was developed in terms of a parametrization as a discrete sum of yukawa terms. This has the advantage of being simple in both configuration and momentum spaces. This parametrization is convenient enough to facilitate its use in many-body calculations. Also, several improvements over the previous version⁹⁾ have been incorporated. Another part of the 3π exchange represented by the A_1 meson is included. The determination of the core parameters is now performed by fitting not only the phase shifts but also the scattering data themselves. The fit was carried out via a two step procedure. First, the best fit to the phase shifts was searched for, and then the results were further tuned by fitting the data themselves. Use was made of the world set of data consisting of 913 data points for pp scattering ($3 \leq T_{\text{Lab}} \leq 330$ MeV) and 2239 data points for np scattering ($13 \leq T_{\text{Lab}} \leq 350$ MeV). This set includes recent measurements on cross sections, polarization, Wolfenstein parameters and spin correlations. Some examples of the fit are displayed in Figs. 4 and 5.

Fig. 4 pp polarization and Wolfenstein parameter A

Fig. 5 np differential cross section and polarization

The fit yields a total χ^2/data shown in Table 2. In this table, these values are compared, for reference with those of the most recent phase shift analysis⁸⁾. The total χ^2/data for the same set of data was also calculated in reference (11) for the Reid soft core potential. The values are also shown in Table 2.

	χ^2/data for pp scattering	χ^2/data for np scattering
Paris	1.99	2.17
P.S.A. ⁸⁾	1.33	1.80
R.S.C.	4.76	9.99

Table 2

To date, we do not know of any theoretical or even purely phenomenological NN potential that has achieved such a degree of accuracy in fitting the data.

In the literature, one still finds NN potential builders who are satisfied with a good comparison of their results with the empirical phase-shifts. We would like to emphasize that, for an accurate quantitative test of models (theoretical or phenomenological), it is more decisive to compare theoretical predictions with experimental data directly rather than through phase shifts. This point is illustrated with the example of the Reid soft core and the Paris potentials. For the fit to phase shifts, the χ^2/data obtained by both of them are very similar, as seen above. On the contrary, when the fit to the data itself is considered, the results are drastically different, as can be seen in Table 2. A phase shift representation is useful and gives a good idea of the overall properties of the NN interaction. It is, however, not constraining enough to put a severe test on the models.

Of course, in the derivation of the Paris potential, the procedure of using theory for the description of the (LR + MR) part and phenomenology for the (SR) part is only meaningful if the theoretical inputs are not washed out by the phenomenological part in the final results. Care was taken in this respect. In Fig. 6 the theoretical ($\pi + 2\pi + \omega + A_1$) exchange potential is compared with the full Paris potential for two examples, the triplet central po-

tential, $T=1$ and the tensor potential, $T=0$. Deviations of the long and medium part from the full potential occur only at distances $r \gtrsim 1$ fm.

Fig. 6 The solid lines refer to the complete potential, the dashed lines to the theoretical $(\pi + 2\pi + \omega + A_1)$ potential

This provides an a posteriori justification to the philosophy adopted from the beginning in the construction of the Paris potential.

This also suggests that, in the framework of the S-matrix theory, we have achieved a reasonable and quantitative understanding of the low energy NN interaction for distances larger than 0.8 - 1 fm, and that any ultimate theory of strong interactions should recover the same results in that region.

3 - Applications to complex nuclei

3.a) The Trinucleon System (${}^3\text{H}$, ${}^3\text{He}$)

Those systems are, of course, the first ones to be studied for a test of the previous two body forces. In this case, given the two body forces, the problem can be solved exactly with the help of large computers. The observables of interest are the binding energies E_B and the form factors.

In Table 3, are listed the values of the ${}^3\text{H}$ binding energy yielded by different potentials, the phenomenological ones like the Reid soft core (R.S.C.) and the V14 potentials, as well as the Paris potential. In comparison with the experimental value, all potentials underbind by 1 to 1.5 MeV.

Potential	E_{KIN} (MeV)	E_{POT} (MeV)	E_{B} (MeV)	References
R.S.C.	{	{	-7.1	J.J. Benayoun et al., Phys. Rev. <u>C23</u> , 1854 (1981)
			-7.022	J.L. Friar et al., Phys. Rev. <u>C25</u> , 1616 (1982)
			-7.232	C. Hadjuk and P.U. Sauer Nucl. Phys. <u>A369</u> , 321 (1981)
PARIS	49.925	-57.157	-7.232	ibid.
vi4	43.034	-50.418	-7.384	J. Carlson et al., Nucl. Phys. <u>A401</u> , 59 (1983)
EXPERIMENT	46.5	-53.5	-7	
			-8.48	

Table 3

The ${}^3\text{He}$ form factor is, in general, correctly described for low momentum transfers, but all models disagree with experiment for $q^2 > 10 \text{ fm}^{-2}$.

3.b) Nuclear Matter

Because of the lack of time, I will skip the applications to finite nuclei and consider the extreme case of infinite nuclear matter. The quantities of interest here are the binding energy per particle E/A and the Fermi momentum k_F at the saturation point. Although infinite nuclear matter is theoretically a simpler system than finite nuclei, the methods of calculating the saturation parameters require various approximations. In the Brueckner theory,

the lowest order leads to the Brueckner-Hartree-Fock (BHF) approximation. Different choices of the single particle spectrum can be made. The conventional choice has the disadvantage of presenting a gap at $k = k_F$. This difficulty is circumvented by the so called continuous choice of the single particle spectrum¹²⁾ or by a model-space approach¹³⁾ which leads also to a continuous single particle spectrum at $k = k_F$. This method is denoted (MBHF) in Table 4. In this table, are shown the saturation parameters calculated with different potentials using different methods.

Potential	E/A (MeV)	k_F (fm ⁻¹)	Method	Reference
R.S.C.	- 9.8	1.36	BHF	Z.Y. Ma, T.T.S. Kuo, Phys. Lett. <u>127B</u> , 137 (July 83)
	<u>-13.3</u>	<u>1.4</u>	MBHF	
M.R.S.C.	-10.5	1.4	BHF	B.D. Day, PRL <u>47</u> , 226 (1981)
OBEP	HM1 -11.8	1.48	BHF	K. Holinde and R. Machleidt, Nucl. Phys. <u>A247</u> , 425 (1975) Nucl. Phys. <u>A256</u> , 479 (1976)
	HM2 -23.5	1.77	BHF	
PARIS	-11.22	1.51	BHF	M. Lacombe et al., Phys. Rev. <u>C21</u> , 861 (1980)
	-11.2	1.5		B.D. Day, PRL <u>47</u> , 226 (1981)
	-11.5	1.5		Z.Y. Ma, T.T.S. Kuo, Int. Conf. on Nuclear Physics, Florence, (I) sept. 83
	<u>-15.5</u>	<u>1.6</u>	MBHF	Ibid.
	<u>-16.1</u>	1.62	BHF	A. Lejeune, M. Martzolf, P. Grangé, Preprint (1983)
	<u>-21^a</u>	<u>1.6</u>	with continuous choice of S.P.S.	
			same	M.A. Martin, M. Dey, Phys. Rev. <u>C27</u> , 2356 (1983)
VI4	-20	1.7-1.8	Variational FHNC	J. Carlson et al., Nucl. Phys. <u>A401</u> , 59 (1983)
Empirical value	-16	1.33		

^a In their paper, Lejeune et al. indicate an error of about 5 MeV in the results of this reference.

Table 4

The table shows that the results obtained with the same method are now consistent with each other. The improved BHF method (MBHF or BHF with a continuous choice of the single particle spectrum) gives, for the Reid soft core potential, too low an energy : $E/A = -13.3$ MeV at about the correct value $k_F = 1.4 \text{ fm}^{-1}$, and, for the Paris potential, a correct value of the energy : $E/A = -16$ MeV but at too large a value $k_F = 1.6 \text{ fm}^{-1}$.

2.c) The NN interaction in Nucleon-Nucleus Reactions

Once the free NN interaction is known, one can try to construct a two nucleon effective interaction in the presence of nuclear medium. Much progress has been achieved during the last few years in the theoretical attempts to construct such effective interactions from the free NN interactions¹⁴⁾. From these effective interactions, calculation of cross sections and polarizations in elastic and inelastic nucleon-nucleus reactions can then be performed. This was done by various groups and comparison made with accurate measurements on (p, p') and $(\vec{p}, p')$ reactions in the energy region $100 \leq E_p \leq 400$ MeV. This provides a test of the free NN interaction inputs and also of methods used to derive the effective interactions. Complete references to these works can be found in reference (14). In Figures 7 - 10, are shown only some examples : $^{12}\text{C}(p, p')^{12}\text{C}$, $^{16}\text{O}(p, p')^{16}\text{O}$ and $^{28}\text{Si}(p, p')^{28}\text{Si}$ for $80 \leq E_p \leq 200$ MeV.

In general, the different interactions (calculations have been performed mostly with the Hamada Johnston and the Paris potentials) can manage to reproduce the cross sections. The behaviour of polarizations, however, varies with the NN potential inputs.

In conclusion of this section one can say that in various applications to complex nuclei the results obtained with the Paris potential compare well

with experiment. This achievement is far from being trivial. To quote only one example, the nucleon-nucleus differential cross sections span several orders of magnitude. Here also, the data are of a very high precision.

Fig. 7 Cross sections and analyzing powers in $^{12}\text{C}(p,p')^{12}\text{C}$.
Data points and calculations are from reference (15)

Fig. 8 Cross sections and analyzing powers in $^{16}\text{O}(p,p')^{16}\text{O}$.
Data points and calculations are from reference (16)

Fig. 9 Cross sections in $^{28}\text{Si}(p, p')^{28}\text{Si}^*$ $5^-, T=0, 9.70$ MeV.
Data points and calculations are from reference (17)

Fig. 10 Analyzing power in $^{28}\text{Si}(p, p')^{28}\text{Si}^*$ $6^-, T=0$, 11.58 MeV.
Data points and calculations are from reference (17)

Conclusions

It is fair to say that the long standing problem of the interaction between two nucleons at low energy still resists any fundamental theory of strong interactions like QCD. On the other hand, as shown in this talk, a *quantitative* understanding has been reached in terms of hadronic (mesonic and isobaric) degrees of freedom, at least for the outer part of the interaction. The crucial role played by the S-matrix theory here is to be emphasized. It provides

a unique framework for carrying out with accuracy fairly complicated calculations.

Recently, it has been conjectured¹⁸⁾ that, at low energies (and for large number of colors), QCD can be approximated by effective lagrangians where quark and gluon degrees of freedom are averaged out. These effective lagrangians are constructed from meson fields and baryons emerge as solitons. The Skyrme model¹⁹⁾ is of this type. The NN interaction has been derived from the Skyrme model²⁰⁾. It is remarkable that some connection can be made between the results obtained and those from the S-matrix theory.

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