

RELATIVISTIC TREATMENT OF THE FEW BODY SYSTEM

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Some specific examples of effects of mesonic degrees of freedom and special relativity in the two- and three-nucleon system are reviewed. For the two-nucleon system a relativistic covariant formulation of the one boson exchange and isobar model is described based on the Bethe-Salpeter equation. Its extension to dynamical equations satisfying three-particle unitarity above one pion production threshold is presented. Moreover, the meson theoretical basis of the Dirac approach for elastic proton-nucleus scattering is discussed using the above mentioned relativistic one boson exchange model.

In the past two decades strong evidence has been presented that a nonrelativistic description of the few nucleon system in terms of pair-wise interaction is not in accordance with the various experimental results. Well known examples are radiative neutron capture and the electro disintegration of the deuteron¹. We review briefly two other cases in view of some recent interesting experimental and theoretical work.

NN interactions which are believed to describe the nuclear force in an accurate way at least up to the one pion production threshold, leads to the underbinding of the triton typically by $1-1\frac{1}{2}$ MeV whereas the secondary maximum in the elastic charge form factor of ^3He is much too low in the theoretical predictions. In table I some recent results are summarized for the case of the Paris and Reid-soft-core (RSC) potentials. The 5-channel calculations contain only the $^1\text{S}_0$, $^3\text{S}_1$ - $^3\text{D}_1$ two-nucleon partial waves potentials while the complete 18-channel analysis has all the components up to angular momentum $\ell=2$ included. The results of the triton binding calculations of refs. 2 and 3 agree very well for the RSC potential. A puzzling point however is that in the Paris case they differ by 0.2 MeV which is greater than the suggested numerical inaccuracy.

Possible explanations for the failure of the nonrelativistic description are the presence of the non-nucleonic degrees of freedom such as mesons and quarks and effects of special relativity. Attempts to explain the differences by the presence of mesonic degrees of freedom have been rather successful. They give rise to effective three-nucleon (3N) forces and so-called mesonic exchange

Table I

The triton binding energy (E_{3H}), position of the dip (Q_{\min}^2) and magnitude of the secondary maximum F_{\max} in the elastic charge form factor of ${}^3\text{He}$ as calculated in refs. 2 and 3.

	5-channels		18-channels		exp
	Paris	RSC	Paris	RSC	
$E_{3H}(\text{MeV})^{(2)}$	-7.48	-7.03	-7.56	-7.24	-8.49
$E_{3H}^{(2)}(\text{MeV})^{(3)}$	-7.303	-7.023	-7.384	-7.232	
$Q_{\min}^2(\text{fm}^{-2})^{(3)}$	14.4	13.7	14.4	13.9	10.6
$F_{\max}^{(3)}$	1.6210^{-3}	1.8610^{-3}	1.6210^{-3}	1.8810^{-3}	710^{-3}

current (MEC) effects. In most analysis carried out up to now this is done in a perturbative way.

Relativistic effects have been studied using minimal relativity in the quasi-potential approach and more recently the Bethe-Salpeter equations⁴. These effects lead to an additional binding of 0.25-0.50 MeV. The study of the 3N force contribution to the triton binding energy has recently received considerable attention^{2,5,7}. For the RSC potential the first order perturbation estimate of Ishikawa et al.² using the Tucson-Melbourne (TM) 3N force⁶ arising from the two-pion exchange gives a value of -0.89 MeV. Their calculations show that it is important to include also the other components of the two-nucleon force than 1S_0 , 3S_1 - 3D_1 i.e. the full 18-channel Faddeev wave function is needed. Moreover, there is a strong dependence on the short range part of the 3N force. Very recently the Faddeev equations have been solved nonperturbatively⁷ and it is found that the first order perturbation can be very bad. For the case of the RSC and TM force a value of -2.3 MeV is found, leading clearly to the overbinding of the triton. From these studies we may conclude that more work is needed on the short range behaviour of the 3N force in order to get reliable answers for the contribution to the triton binding energy and that we may have to go beyond a perturbational treatment.

In the case of the elastic ${}^3\text{He}$ charge form factor the largest MEC contribution arises from the so-called pair-excitation graph where a $N\bar{N}$ pair is excited (fig. 1)⁸. The $N\bar{N}$ vertex is obtained from the NN vertex by assuming that the corresponding form factor is a Lorentz scalar, depending only on the four-momentum square of the pion. Such a term can be viewed as arising from the

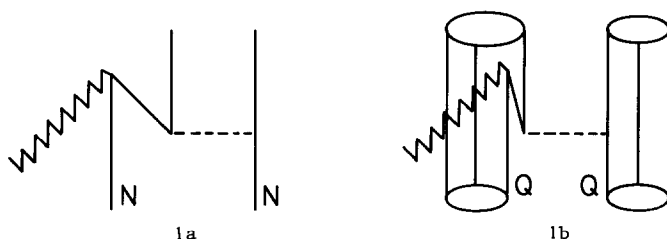


FIGURE 1

The pair term contribution to the em vertex in the nucleonic (1a) and constituent quark (1b) picture.

propagation of a nucleon as a Dirac particle and hence as an effect of special relativity. On the other hand it is also connected to the NN dynamics because a virtual meson is exchanged between two nucleons. Although the estimates of the pair terms are sensitive to the cutoff mass in the NN π vertex it moves the calculated charge form factor of ^3He in the right direction. In fig. 2 are shown the results from ref. 8 for the case of the RSC interaction. Assuming that a

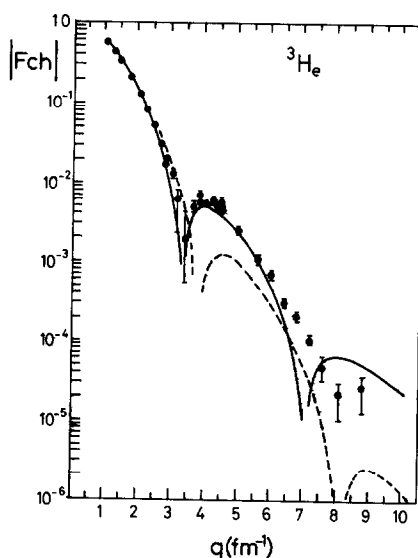


FIGURE 2

The nonrelativistic (---) and complete (—) results including the pair term for the ^3He charge formfactor. Exp points are from ref. 9.

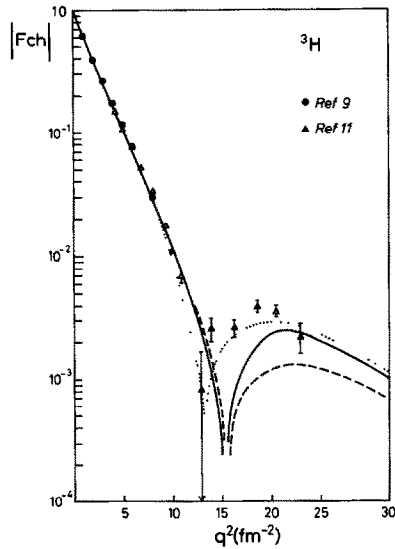


FIGURE 3

Calculated results for the ${}^3\text{H}$ charge form factor using the nucleon (—) and quark picture (...). Nonrelativistic result is given by the dashed line.

constituent quark picture holds the pair term can be estimated from a graph like fig. 1b¹⁰. Similar results are found for the 3 charge form factor, but there is a distinct difference in the prediction of the ${}^3\text{H}$ charge form factor with respect to the position of the dip. The calculated results are shown in fig. 3. In the nucleonic model the dip is virtually not shifted by the MEC contributions, whereas in the constituent quark model it moves substantially to lower q values. The preliminary results of the recent Saclay experiment¹¹ are also shown in the figure. They tend to favour the constituent quark model. The MEC effects such as the pair term should be considered critically not only because of the strong dependence on the cutoff mass in the $\text{NN}\pi$ vertex, but basically, since the MEC effects are connected to the NN dynamics, a consistent treatment is required. In particular, the dynamical effects on the wave function due to relativity should be accounted for.

One of the simplest systems to study the problem of consistent treatment of both the dynamics and electromagnetic structure is the two-nucleon system. To describe the dynamics of such a system, we assume that for the energy region we are interested in, the conventional picture holds i.e. the degrees of freedom are nucleons and mesons and that we have an effective meson theoretical basis for the NN interaction. Our starting point is the field theoretical Bethe-

Salpeter (BS) equation for NN scattering¹². For the T-matrix it has the form

$$T = V + VST \quad (1)$$

where S is the two-nucleon Green's function

$$S = (\not{p}_1 - m_N)^{-1} (\not{p}_2 - m_N)^{-1} \quad (2)$$

and V is the BS kernel consisting of the set of all irreducible graphs. To simulate the nucleon-nucleon interaction we assume that it can be represented by the one boson exchange model. The mesons taken in the actual calculations are $\pi, \sigma, \rho, \omega, \eta$ and δ . To regularize the interaction a form factor of the type

$$f(t) = \left[\frac{\Lambda^2}{\Lambda^2 - t} \right]^\alpha \quad (3)$$

is used at each meson-nucleon vertex where t is the four momentum square of the meson and α is taken to be 1 in most calculations. The coupling parameters can be chosen such that we get a reasonable fit to the NN data at energies up to 250 MeV. It is clear that we should consider such a model at most as an effective theory. The equations satisfy two-particle unitarity up to the one pion production threshold and are relativistic covariant. Also the Pauli principle of identical fermions is automatically satisfied.

Within such a model the electromagnetic properties of the deuteron can be discussed¹³. Using the relativistic impulse approximation the various em form factors can be calculated. The em vertex function of the nucleon is assumed to have the on-mass-shell form

$$\Gamma_\mu(q) = \gamma_\mu F_1(q^2) + \frac{i}{2m_N} \sigma_{\mu\nu} q^\nu F_2(q^2) \quad (4)$$

q being the photon momentum. With this form and our choice of the BS-kernel gauge invariance is satisfied for the em deuteron current. The deuteron wave function in this relativistic model has a component with a negative energy spinor state and as a consequence the resulting em form factors among others also contain the pair term contribution. In addition there are also corrections to the positive energy components of the wave function from the intermediate states where the nucleon can propagate as a negative energy state. Explicit analysis in this model shows that the corrections to the non-relativistic results are not as large as the perturbational pair term estimate gives, indicating that the dynamical corrections tend to cancel the pair term contributions. The same conclusions are reached using a quasi-potential approach where

one of the nucleons is put on mass shell^{13,14}. Recently the magnetic form of the deuteron has been measured up to $q^2 = 28 \text{ fm}^{-2}$ ¹⁵. The results are shown in fig. 4 together with the pair term included perturbatively and the consistent

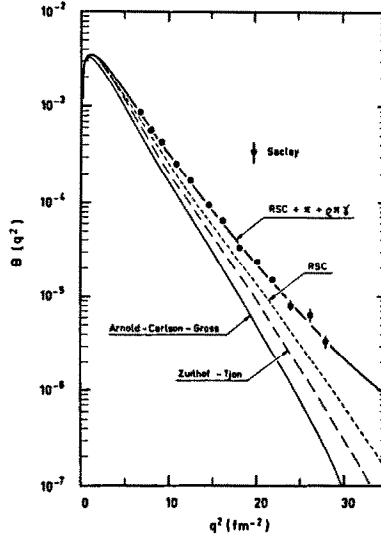


FIGURE 4

Magnetic form factor of the deuteron.

treatment using the BS and quasi-potential equations. In the deuteron case we have an additional important contribution from the $\pi\gamma\gamma$ -graph, which is not included in the nonperturbative calculations¹⁶. From this figure we again see that the MEC corrections are improving the agreement with experiment, but that the non-perturbative treatments still lead to a sizable discrepancy. A possible reason for the difference may be due to the isobar components of the deuteron. We also see comparing the results from refs. 13 and 14 that there is a certain model dependence on the details of the choice of the interaction kernel. From the above model studies we may infer that the dynamical effects can be significant. As a result it would be interesting to carry out a careful analysis for the tri-nucleon system to see whether also in that case the dynamical effects are important.

We now turn to the discussion of the two-nucleon interaction at intermediate energies say up to $1 \text{ GeV } T_{\text{lab}}$. This subject has drawn considerable attention because of the discovery in polarized pp scattering experiments of certain resonance structures at around $600 \text{ MeV } T_{\text{lab}}$ ¹⁷. In fig. 5 the observed energy

dependence of the individual cross-sections and $\Delta\sigma_L = \sigma_{\text{tot}}(\vec{\uparrow}) - \sigma_{\text{tot}}(\vec{\downarrow})$ are shown. The possible origin of this structure may be attributed to the presence of exotic dibaryon resonances or explained within a more conventional approach with mesons and nucleons. In particular, the latter possibility has been explored in some detail by several groups. Here we would like to review one of them.

At intermediate energies a relativistic treatment of the nucleons become necessary. In addition pion production becomes possible and as a result a dynamical theory should also describe this appropriately. At the energies we are interested predomi-

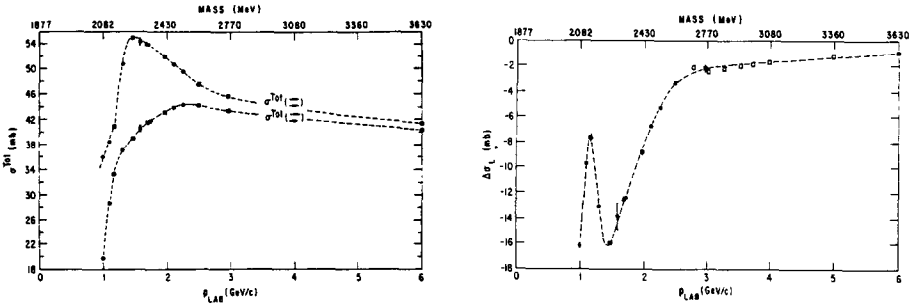


FIGURE 5

Energy dependence of $\sigma_{\text{tot}}(\vec{\uparrow})$, $\sigma_{\text{tot}}(\vec{\downarrow})$ and $\Delta\sigma_L$ (from ref. 17).

nantly one pion production takes place through the P_{33} πN -resonance. One typical type of approach has been to put a strong emphasis on the three-particle aspects by formulating Faddeev-like equations for the πNN system^{18,19}. These approaches have the drawback that there are difficulties with satisfying the Pauli principle and which is repaired in a rather artificial way. We have followed a different procedure by starting from the Bethe-Salpeter equations for two nucleons, thereby emphasizing the two-particle aspects²⁰. The theory satisfies manifestly the Pauli principle and is relativistic covariant. In addition to the use of the one boson exchange mechanism for the driving force the nucleon states are assumed to be coupled to the Δ isobar at 1236 MeV. In fig. 6 the diagrammatic representation is shown of the resulting Bethe-Salpeter equations for NN scattering coupled to the Δ -degrees of freedom. In this relativistic extension of the isobar model the transition interaction is assumed to be given by one pion and rho exchange. For practical reasons the calculations have been carried out by dropping the negative energy N and Δ spinor states. Effects of

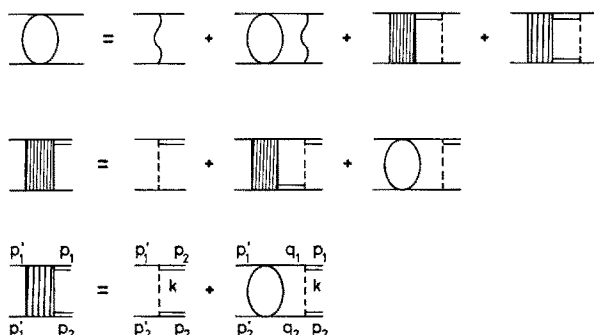


FIGURE 6

Coupled BS equations for NN scattering.

these states on the physical NN scattering are expected to be small and to give rise to modifying slightly the meson-nucleon coupling constant strengths. The Δ is treated as a Rarita-Schwinger propagator with a complex mass given by

$$\mu_{\Delta} = m_0 - \frac{i}{2} \Gamma(q) \quad (5)$$

with $m_0 = 1236$ MeV and for the width Γ the Bransden-Moorhouse²¹ parameterisation is used

$$\begin{aligned} \Gamma(q) &= 0 & q^2 < 0 \\ \Gamma(q) &= 2\gamma(\hat{q}R)^3/[1+(\hat{q}R)^2] & q^2 > 0 \end{aligned} \quad (6)$$

$$\hat{q} = q/m_{\pi} \quad \gamma = 71 \text{ MeV} \quad R = 0.81$$

The πN three-momentum q is related to the πN invariant mass by

$$q^2 = \frac{[s_{\pi N} - (m_{\pi} - m_N)^2][s_{\pi N} - (m_{\pi} + m_N)^2]}{4s_{\pi N}} \quad (7)$$

In most calculations we have made the so-called fixed energy approximation i.e. following VerWest²² it is assumed that in the $N\Delta$ system the Δ picks up all the available energy

$$s_{\pi N} = (\sqrt{s} - m_N)^2 \quad (8)$$

where \sqrt{s} is the total NN energy. In fig. 7 are shown the results for the reso-

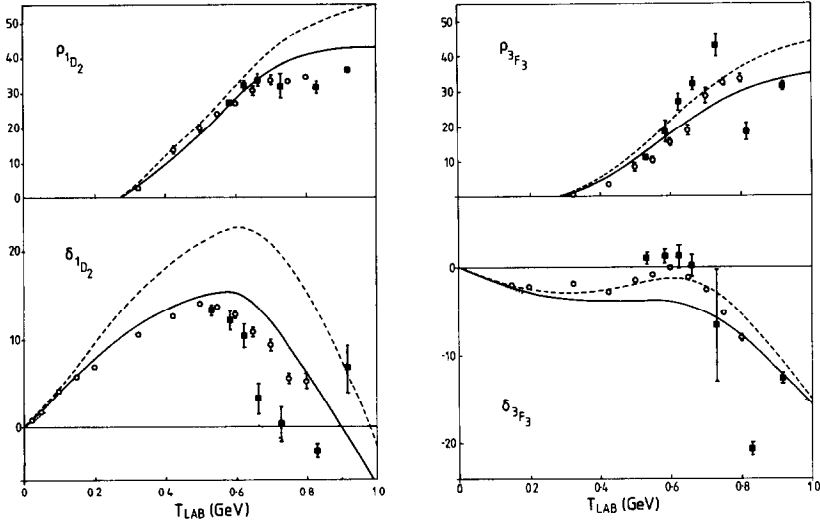


FIGURE 7

NN phase parameters for the 1D_2 and 3F_3 channels. The solid curve is for $f_{N\Delta\pi}^2/4\pi = 0.23$, the dashed curve for $f_{N\Delta\pi}^2/4\pi = 0.35$ and the dotted curve is the result when only NN channels are kept. The exp phase shift analysis are from ref. 23.

nating channels 1D_2 and 3F_3 for the case that the $\rho N\Delta$ coupling is set to zero and the $\Delta\Delta$ states are neglected. From this we see the phase parameters are well described. The other partial waves are also in qualitative agreement, with the exception that more state dependence is needed in the p-waves. Switching on the $\rho N\Delta$ coupling leads to an improvement in these partial waves, but less inelasticity is then found in the 1D_2 and 3F_3 channels.

In the experimental phase shift analysis some theoretical input is needed for the peripheral NN phase shifts. Above pion production threshold the one pion exchange diagram is not sufficient to represent them in view of non-negligible inelasticity. One may hope that dynamical model predictions are reliable enough to be used for the high partial waves. In the literature sizable model dependence has however been found. In particular in the model discussed here the inelasticity for these high partial waves is rather high as compared to the three-body models. Much of the difference can be removed by replacing eq. (8) by the physically more acceptable one

$$s_{NN} = \left(\sqrt{s} - \sqrt{p_1^2 + m_N^2} \right)^2 \quad (9)$$

where p_1 is the three momentum of the nucleon²⁴. However still some model dependence is present. Such uncertainties in the peripheral waves may affect the reliability of the resulting phase shift analysis.

The above described model has the drawback that above inelastic threshold unitarity is violated. However the model can be extended to also satisfy three-particle unitarity²⁵. This is done by renormalizing the nucleon propagator in lowest order by the πN bubble self energy diagram. Also if we would like to describe the observables in the pion production experiments a more detailed description of the P_{33} -resonance would be necessary. For this we have used a two-particle model. The pion nucleon scattering is described by the set of diagrams given by those in fig. 8.

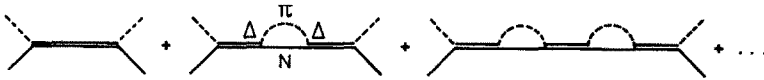


FIGURE 8

Model for P_{33} πN scattering

In our initial attempts to use the $N\Delta N$ vertex function of the OBE one failed to describe the Chew-Low plot of P_{33} -scattering. The main reason is that such a form factor gives rise to a too large effective range. An excellent description was found when we modified the vertex function by introducing a scattering function g_{scatt}

$$\Gamma_{N\Delta N} = f_{\text{OBE}}(k^2) g_{\text{scatt}}((p-2k)^2) \quad (10)$$

where the argument of g_{scatt} is assumed to be on shell i.e.

$$(p-2k)^2 = (\vec{p}-2\vec{k})^2 - (E_{\vec{p}-\vec{k}} + \omega_k)^2 \quad (11)$$

with $E_{\vec{p}} = \sqrt{\vec{p}^2 + m_N^2}$ and $\omega_k = \sqrt{\vec{k}^2 + m_\pi^2}$. In fig. 9 is shown the Chew-Low plot $R_{\text{CL}} = q^3 \cot \delta_{33} / m_\pi^2 \omega_L$ of the P_{33} -channel for the various models used to describe the Δ propagator. With this unitary model we may calculate the NN observables. Some preliminary results are shown in fig. 10 for the 1D_2 and 3F_3 channels. From this we see that the behaviour is similar as previously with the only exception that the inelasticity is much less pronounced near one pion production threshold. This is a reflection of the fact that a two-body model for the Δ gives rise to an effective smearing out of the Δ width, analogous to what we find if we use eq. (9). Since the above theory contains an explicit model for pion production, it

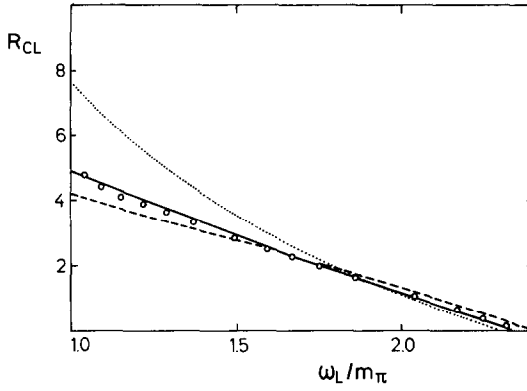


FIGURE 9

Energy-dependence of R_{CL} using the Bransden-Moorhouse parameterisation (---), the model of ref. 19 (...) and this model (—), where ω_L is the pion lab energy.

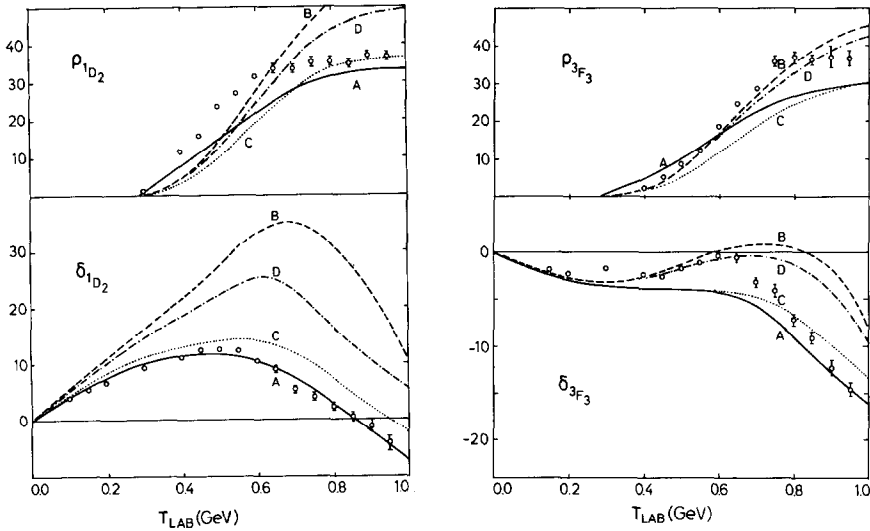


FIGURE 10

1D_2 and 3F_3 phase parameters using the unitary model. Curves B, C and D are calculated with the same coupling constants as for the non-unitary model (curve A) except $(\lambda_{N\pi\Delta}^2/m_N^2, f_{N\rho\Delta}^2/4\pi) = (3.5, 0), (3.5, 8)$ and $(1.5, 0)$.

will be interesting to see what the pion production predictions are. Although it basically has the same physical ingredients as the Faddeev-like approaches such as of Kloet and Silbar, it has the major advantage not to violate the Pauli principle and some retardation effects of the meson exchanges are included.

As noted previously the influence of the negative energy spinor states of the nucleons is expected to be small on the physical NN scattering. Their presence can essentially be compensated by small changes of the coupling constants if we want to get the same phase parameters back. However, since such a relativistic theory for NN interaction leads necessarily to non-vanishing T-matrix elements between positive and negative energy spinor states of the nucleons, these elements can in principle affect the properties of composite systems such as nucleon-nucleus scattering. It is precisely this aspect which has received considerable attention recently in the highly successful Dirac description of nucleon-nucleus scattering. At intermediate energies it is now common practice to describe elastic nucleon-nucleus scattering by an optical potential in the impulse approximation. To construct this optical potential for the case that we assume that the nucleons can be described as a Dirac particle, the NN T-matrix is needed between positive and negative energy spinor states. In most studies the basic assumption is made that the T-operator in Dirac space can be represented by the five well-known β -decay invariants S, V, T, A and P, the coefficients of which can be determined from the physical NN scattering amplitudes between positive energy states²⁶. In so doing the complete NN T-matrix is determined. However it should be realized that the five β -decay invariants do not form a complete set. To determine the complete T-matrix the detailed dynamics of the NN system is needed, not only the physical NN scattering matrix elements. Such a dynamics is given by the relativistic model discussed here either in the BS or quasi-potential formulation. Given this model the complete T-operator is uniquely determined. The analysis of the most general representation for the NN T-matrix has been carried out²⁷. Using the relativistic model in the quasi-potential approximation, the Dirac optical potential has been constructed in coordinate space. The potentials are in general very different in strength from those calculated using the β -decay invariants assumption especially at lower energies. The major difference can be traced back to the treatment of the pion, where the β -decay invariants representation favours a pseudo scalar coupling of the pion to the nucleon. In fig. 11 are shown the effective scalar and vector potentials for the case of ^{40}Ca at 181 MeV T_{lab} . Although the shape and strengths of the optical potentials in the two cases are very different one finds qualitatively similar behaviour for the observables of

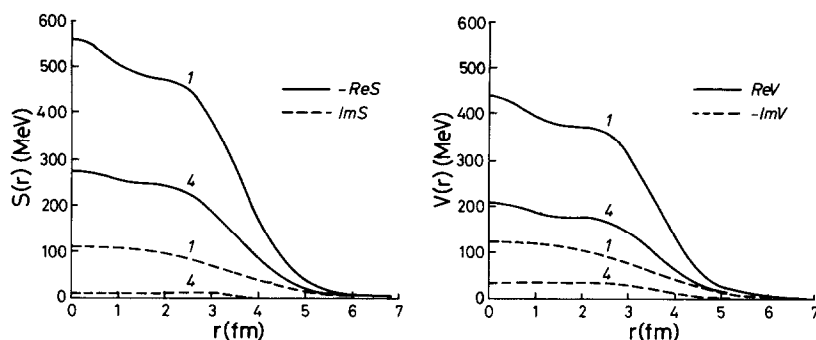


FIGURE 11

Effective scalar and vector parts of the optical potentials at 181 MeV T_{lab} using the β -decay invariants representation (curve 1) and the meson theoretical model (curve 4).

elastic proton-nucleus scattering. In general the predictions of the spin observables in the Dirac approach are remarkably close to the experiment, in contrast to a non-relativistic analysis. As compared to the nonrelativistic treatment, the major theoretical difference is the presence of a contact term, due to the negative energy state components of the nucleon-nucleon T-matrix.

In conclusion, various examples have been discussed about the importance of including the mesonic degrees of freedom and special relativity. In the majority of cases discussed the relativistic effects are due to the presence of non-vanishing matrix elements between the positive and negative energy states. The general trend is that the theoretical predictions come closer in agreement with the experiments. Although such a picture seems to be applicable, the agreement may be fortitious. In particular not all studies have paid enough attention to a consistent treatment of the various effects. Also often alternative explanations are possible like medium corrections in the case of elastic p-nucleus scattering and the presence of quark degrees of freedom in the few body system.

It is clear that a theory consisting of mesons and nucleons can at most be considered as an effective theory. If such a picture holds at intermediate energies it will be extremely interested to understand from a more fundamental theory like QCD how such an effective theory can be derived.

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