A STUDY OF NN PHASE-SHIFT CALCULATIONS IN A QUARK POTENTIAL MODEL

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Great advances have been made in recent years, through the gauge symmetry models, in our understanding of three (electromagnetic, weak and strong) of the four (with gravity) fundamental interactions recognized in nature[1]. Since nuclear physicists can only ignore these advances at great peril to their subject, it is particularly encouraging for me to attend this workshop designed specifically to address the new facets of our field.

Clearly one of the questions that must be asked is what new insights into the structure of nuclei, and into reactions involving nuclei, do these new concepts yield. The question involves discerning how large a role the internal structure of nucleons (and hence higher resonances) plays in determining properties of nuclei. At Chalk River, together with my colleagues J. LeTourneux and B. Lorazo from the Université de Montréal, we have been considering the question with regard to the interaction between nucleons.

Of course, quantum chromodynamics (QCD) being the accepted fundamental form of the strong interaction (at least for the moment), should be responsible for the whole of the strong interaction between nucleons. In practice, the complexities of QCD will surely prevent us from describing the whole of the NN-interaction starting from the fundamental Lagrangian. Fortunately, there appears to be a possible "symbiosis" between the new ideas introduced by QCD and the old meson exchange picture of the NN-interaction given by Yukawa. QCD has the property of being "asymptotically" free at high energies i.e. the short-distance interaction between quarks can be treated perturbatively. It is, therefore, in the short-distance behaviour of the nucleon-nucleon force that we should hope to recognize QCD effects first. This is the very part of the force that has traditionally[2] been the most difficult to describe and which is often simulated by high momentum regularisation[3,4] or a phenomenological hard core potential[5,6]. At high energies QCD is confining and even today, with the vast amount of computer time spent in the lattice gauge calculations, we do not have a successful description of this mode. The confinement mode does not mean that quarks cannot leave the baryon, only that colour is confined. This seemingly illogical statement (since quarks carry colour) is possible since the quark, on leaving the environs of a baryon, can polarise the vacuum to form an additional quark-antiquark pair (Fig. 1): together with the original quarks the physical system can now resemble an observable baryon-meson pair. Thus confinement is intimately tied to meson production - and meson exchange at long distances is the most successful part of our traditional description of the nuclear force. The problem, as I see it, is how to successfully marry a perturbative QCD description of the short range part of the NN-interaction, with the long range meson exchange. How short is short and how long is long? It is to be hoped that the two approaches overlap at some range so that we can go from one to the other.

In Canada we have concentrated our efforts up to now on the short range components. More detail beyond that given below appears elsewhere[7-9]. We have asked whether we can correlate the known properties of nucleons (N) and deltas (Δ) with the known properties of the NN-interaction at short distances - and how accurately can we determine this correlation. Our work has been stimulated by the earlier studies of Isgur & Karl[10] who showed that the properties of single hadrons could be correlated by a non-relativistic potential model. Although the non-relativistic aspects of the model are surprising, the success suggests that the short range behaviour of the NN-interaction may be studied in the same model. Our present approach follows that of Oka & Yazaki[11] and is an outgrowth of my earlier studies[12,13]. Although we make extensive use of the fractional parentage techniques[12] the generator coordinate and resonating group techniques now used are superior to, and should be considered to supersede, the old Born-Oppenheimer approach[13].

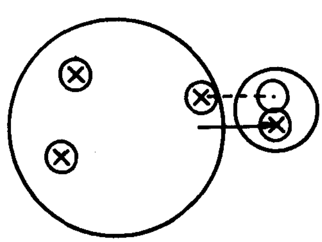

Fig. 1. A schematic diagram depicting the polarisation of the vacuum into a quark-antiquark pair when a quark leaves the baryon thus yielding an observable baryon and meson.

In the generator coordinate (GC) approach[14] we start with the ansatz that the eigensolutions to the Schrodinger equation,

$$H\Psi = E\Psi , \tag{1}$$

can be approximated by

$$\Psi = \sum_{\alpha} \int \phi_{\alpha}(\underset{\sim}{x};\underset{\sim}{R})\ f_{\alpha}(\underset{\sim}{R})\ d\underset{\sim}{R} . \tag{2}$$

Here $\phi_{\alpha}(\underset{\sim}{x};\underset{\sim}{R})$ is a cluster state representing six quarks in two three-quark clusters in oscillator wells separated by a distance $\underset{\sim}{R}$. All other coordinates are described schematically by $\underset{\sim}{x}$. The function $f_{\alpha}(\underset{\sim}{R})$ represents (crudely) the relative wavefunction of the wells and the parameter α represents the various channels (NN, NΔ, CC etc.) in terms of which the solution is to be represented. We write CC for a "hidden colour" state[12,13] which is a colour singlet six-quark state in which each three-quark cluster is colour octet.

Actually the function Ψ is equivalent to that in the resonating group (RG) approximation,

$$\Psi = \sum_{\alpha} \chi_{\alpha}(\underset{\sim}{x})\ \ g_{\alpha}(\underset{\sim}{\rho}) , \tag{3}$$

where $\underset{\sim}{x}$ are internal coordinates and $\underset{\sim}{\rho}$ is the distance between the clusters. The function $g_{\alpha}(\underset{\sim}{\rho})$ is the relative wave function of the clusters which, for the α = NN channel, will be written in terms of the phase shifts for scattering solutions. We have used both the GC and RG techniques and have got identical results. In general we have found the RG approach to be numerically more stable. The problem is to solve the Schrödinger equation with the ansatz in eq. 2 or eq. 3 for the unknown $f_{\alpha}(\underset{\sim}{R})$ or $g_{\alpha}(\underset{\sim}{\rho})$ subject to given boundary conditions for the various channels. Thanks to a proof by deTakacsy[15], we know that the functions $f_{\alpha}(\underset{\sim}{R})$ and $g_{\alpha}(\underset{\sim}{\rho})$ have similar forms for large values of their arguments.

The Hamiltonian[8] is chosen to have a central confining term $v_c(r_{ij})$ and a spin-spin interaction introduced to describe the splitting between the N and Δ states. Thus

$$V(r_{ij}) = \sum_{i<j} \lambda_i \cdot \lambda_j \ [v_c(r_{ij}) + v_{\sigma}(r_{ij})\ \sigma_i \cdot \sigma_j] \tag{4}$$

where λ_j^{α} are the (α = 1,2,$\cdots$8) generating operators of the SU_3 colour group and $\lambda_i \cdot \lambda_j$ denotes scalar product. For simplicity we take

$$v_c(r_{ij}) = A \exp(-r_{ij}^2/\beta^2) + Br_{ij}^2 + C \tag{5a}$$

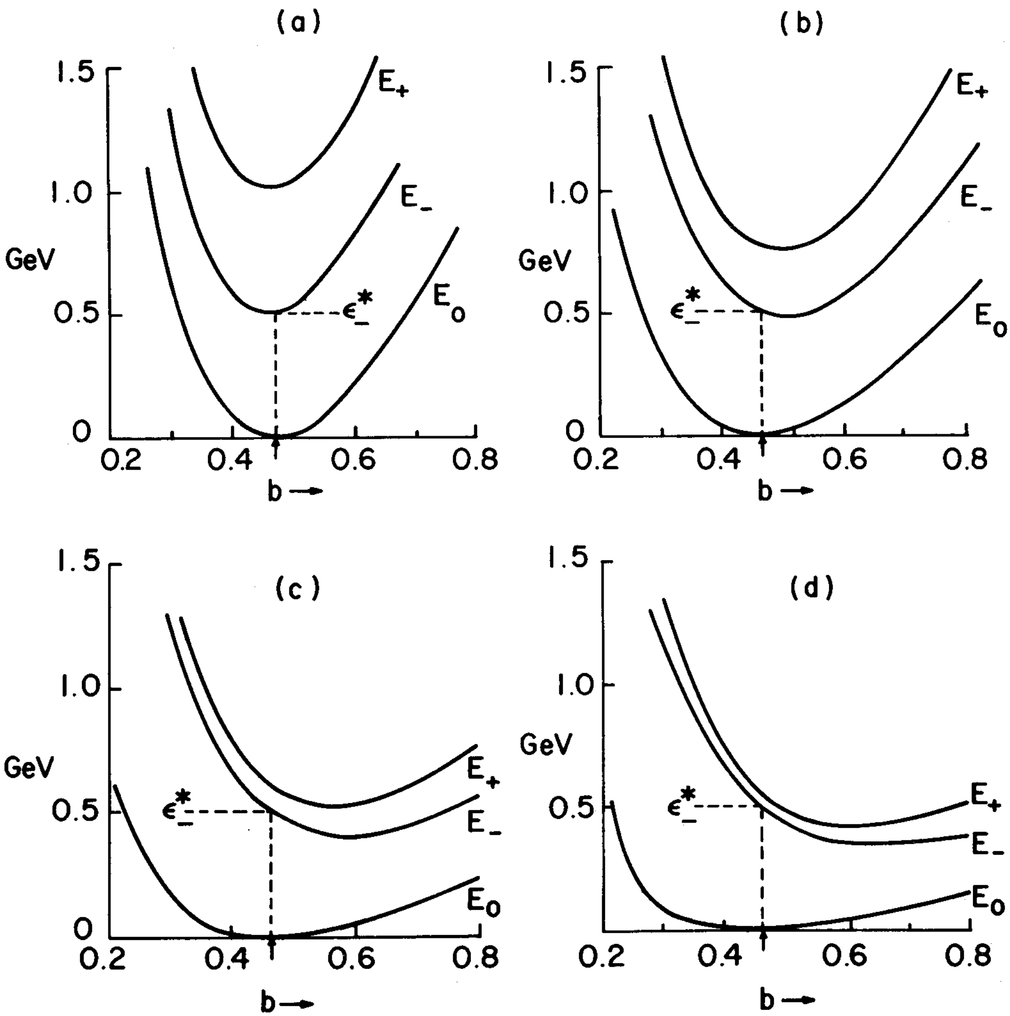

Fig. 2. Variational curves for the mean ground state (E_0), negative parity state (E_-) and excited positive parity state of [3] symmetry with force parameters chosen such that ($E_- - E_0$) at $b = b_0$ fits experiment. Shown for various values of E_+ (see text).

and

$$v_\sigma(r_{ij}) = D\ \delta(r_{ij}) \tag{5b}$$

where, in the confining term, the Gaussian is introduced so that we can vary the mean energy (in a variational calculation) of the excited positive parity states of the N and Δ relative to the mean energy of the

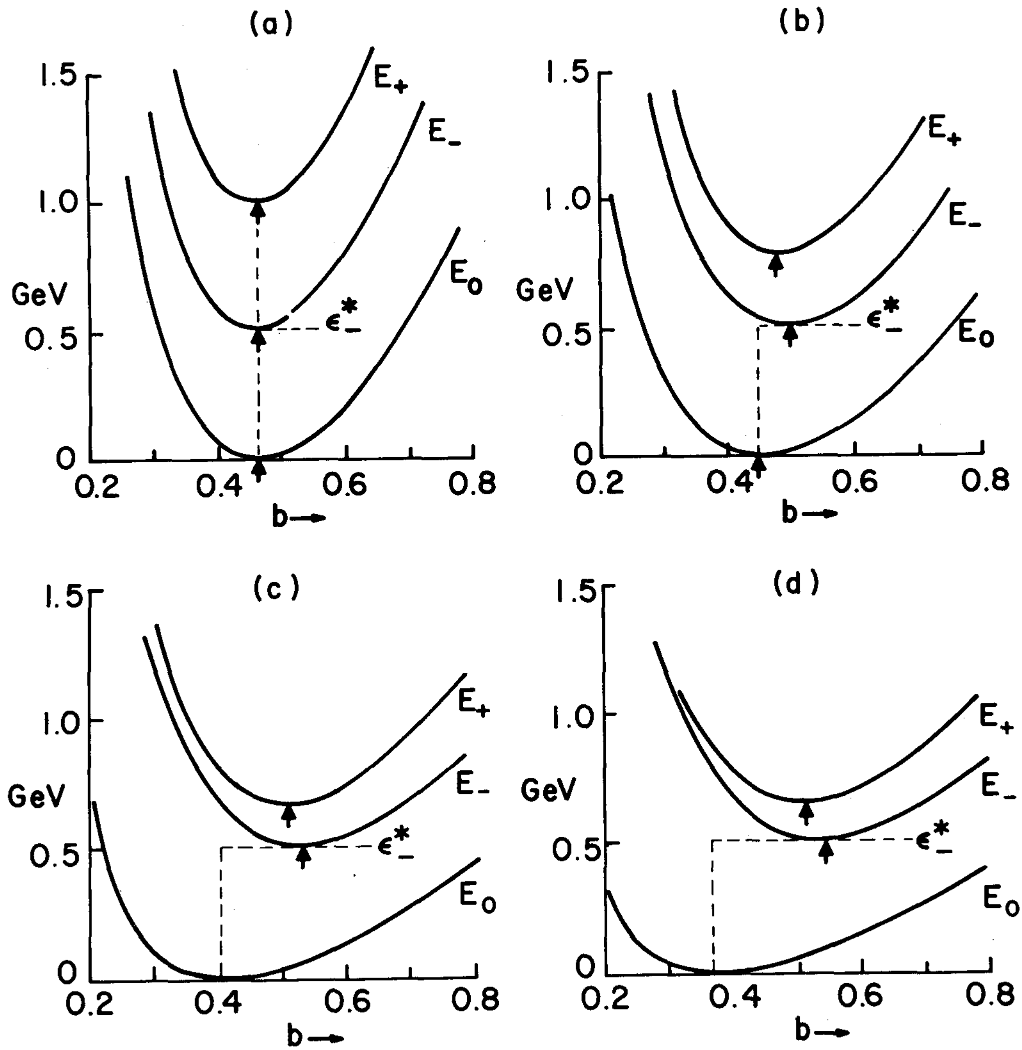

Fig. 3. As in Fig. 2 but where the difference between the minima of the curves for E_- and E_0 fit experiment.

excited negative parity states. By mean energy, we mean that in the absence of the spin-spin interaction.

It is crucial that harmonic oscillator states be used in the GC- or RG-approach. It is natural therefore to choose parameters of the Hamiltonian such that three-quark oscillator states represent the eigensolutions of the baryon spectrum in a variational calculation treating the oscillator parameter (b) as the variational parameter.

This requirement does not determine the parameters of the potential in a rigorous way. Thus the parameters could be chosen such that only the mean energy (E_0) of the ground state (1086 MeV) is variationally stable ($b = b_0$) and the mean energy (E_-) of the set of lowest negative parity states fitted to the experimentally observed value (~1600 MeV) at the same value of $b = b_0$ (c.f. Fig. 2). We refer to this type of fit by the Roman numeral II. Alternatively, we could demand fits to the experimental spectrum at the variational minima of both the ground and negative parity states (c.f. Fig. 3): then the variational parameters at the minima need not be the same. We refer to this type of fit by the Roman numeral I. The stability of the ground state - and whether the negative parity states and ground states minimise at the same or different points - depends on the mean energy (E_+) of the excited positive parity states of [3] orbital symmetry. If these latter states happen to have twice the excitation energy of the negative parity states, the spectrum is "oscillator like", the parameter A in eq. 5 is zero and all states minimise with the same value of b (see Fig. 2 and 3 for case (a)). As the value for the excited positive parity states decreases (cases b, c and d in Fig. 2 and 3), minima for the various states occurat different values of b and, moreover, the minima become "softer" to variations in b (i.e. smaller curvature). Experimentally the mean energy of these excited positive parity states (close to fit d) is almost degenerate with the negative parity states and this is not only the hardest to fit, but leads to a very "soft" ground state. A most undesirable state of affairs.

We have investigated whether the phase shifts (δ) are at all dependent on the above features. In Figs 4 and 5 we show the S-wave phase shifts for extreme values of the parameters i.e. (a) (an oscillator-like baryon spectrum) and Id and IId (which yield the observed baryon spectrum in a variational calculation). The calculation was for the three channel (NN,$\Delta\Delta$,CC) approximation where the channels involve the orbital symmetries found in the NN-channel at large nucleon separation[12]. Similar approximations are taken by Faessler et al.[16-18]. As is seen in Figs. 4 and 5, substantial changes (~50%) can result, warning us that the model is not to be trusted for quantitative results in its present form. Nevertheless, the phase shifts are negative for all energies (similar features are found for the higher partial waves) in accord with what has been deduced about the nature of the short range interaction[4]. The phase shifts are of comparable magnitude (to within a factor of 2) to those calculated from the ω+ρ-exchange used in the Bonn potential[3,4]. We conclude that the quark contribution at short ranges is not negligible and cannot be ignored.

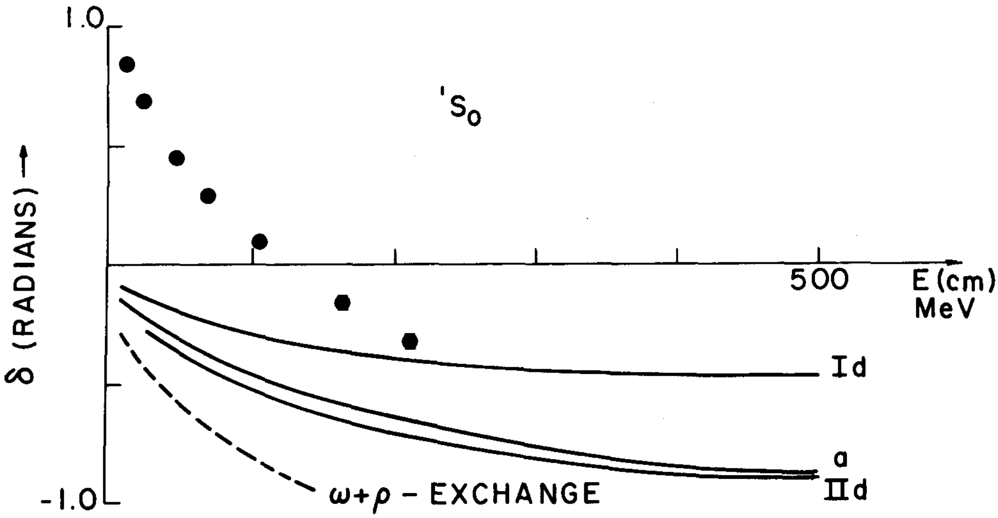

Fig. 4. $^1S_0$ phase shifts from the quark potential calculation with three different potentials. Phase shifts from the experimental scattering data are shown by error bars[19].

The negative phase shifts have been interpreted as those resulting from a phenomenological, local, repulsive potential at short range. The character of this phenomenological potential can be deduced by looking at the wave shift $(-\delta/k)$ where $(\hbar k)^2/M_N = E_{CM}$ (c.f. Figs. 6 and 7). For an infinite hard core repulsion the wave shift is independent of k and equal to the hard core radius. For a soft-core repulsion the wave shift decreases with k as shown in Fig. 6 where the $^1S_0$ wave shift with Force IId could be fitted for $k < 1.5$ MeV by a soft core with height 513 MeV and range ~.63 fm. With some of the forces used the wave shift increases with k for $k \gtrsim 0$ MeV and this indicates some effective attractive potential or a momentum dependent repulsion. It would be nice if the local potential could be deduced directly from the quark calculation, but we argue (c.f. ref. 7) that this cannot be done unambiguously, and therefore, attempts that do so, do not seem to have physical relevance.

We conclude by considering whether the quark potential model is capable of yielding positive phase shifts at low energy in greater accord with experiment. Recent calculations by Maltman & Isgur[20] suggest that this is indeed possible. In a variational calculation for

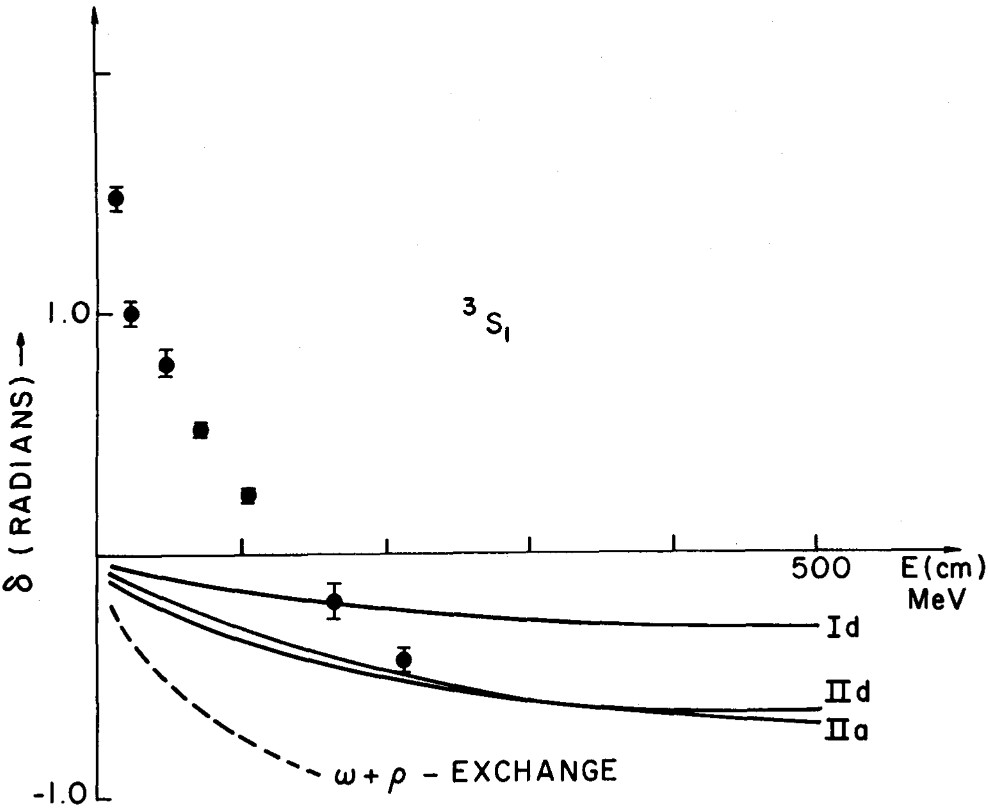

Fig. 5. As in Fig. 4 but for $^3S_1$.

the deuteron ground state, Maltman & Isgur found significant attraction, equivalent to that of a central attractive potential of intermediate range, from certain (additional) six-quark, hidden-colour (CC) states. These are the configurations that also lead to the long range attractive van der Waals force. Although this latter effect must be a spurious product of the potential model (as discussed by Greenberg & Lipkin[21]), the intermediate range attraction is of the magnitude of that of the sigma exchange in meson exchange models[3,4]. We suggest that this is no accident and that the two models are, at this intermediate range, describing the same physical feature. We argue that the separation of a CC state must, at some intermediate range, emit (colour octet) gluons which can then decay into mesons (c.f. Fig. 8). The gluons carry away the colour-octet nature of the hidden colour states

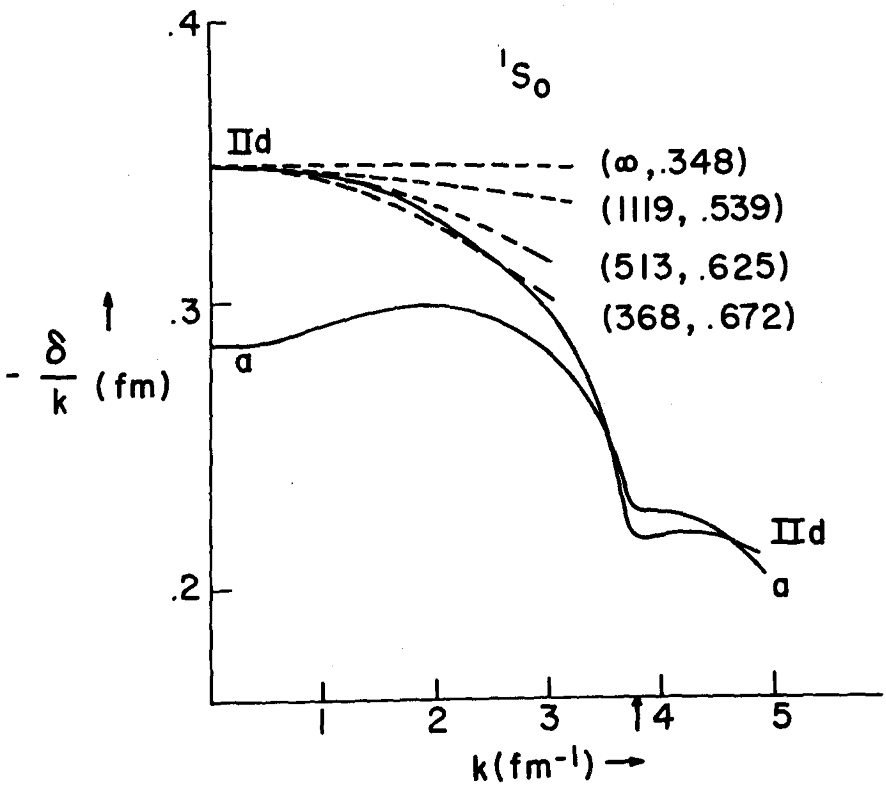

Fig. 6. $^1S_0$ wave shifts from the quark potential calculation for various assumed potentials. The dashed curves are the wave shifts from various local repulsive core potentials with height and range (V_0 (MeV), a (fm)).

leaving colour singlet baryons. Thus the hidden colour degrees of freedom may just be the short range manifestation of some of the mesonic degrees of freedom. The non-relativistic potential model, not being a field theory, cannot describe this equivalence (hence the spurious long range van der Waals force) and it is not clear at the moment how the model can be modified to accommodate it. To leave these hidden colour configurations out of the phase shift calculation (as we have done up to now) may be throwing away the significant medium range attraction in an effort not to have the spurious long range van der Waals interaction. We are now attempting the RG-calculation including these configurations but we cannot tell at this stage whether a relevant calculation is feasible.

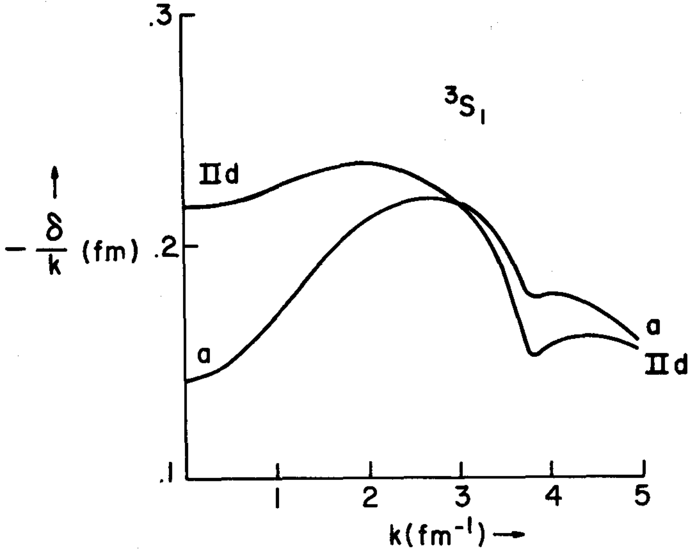

Fig. 7. $^3S_0$ waveshifts.

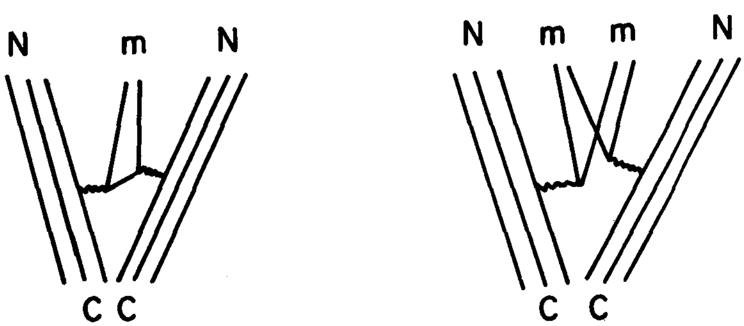

Fig. 8. A schematic diagram illustrating how the "fissioning" of a hidden-colour state leads to colour singlet baryons and mesons.

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