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A NEW LOOK AT THE NUCLEAR FORCE*†

Pierre Noyes

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

Once the boson resonances were discovered, the first part of the Taketani program—the calculation of the peripheral region of the nuclear force—achieved a quantitative success. Calculations of the dynamical (two-pion-exchange) region have proved much more difficult. By 1975 increasingly sophisticated dispersion-theoretic calculations coupled with increasingly accurate measurements of $\pi\pi$ parameters have led to convergence of the predictions made by the two most persistent groups (Stony Brook and Paris). These predictions agree with each other, and with much experimental evidence. A lot of the uncertainty in the phenomenological ω-meson cutoff has been removed by fitting a single vector meson renormalization parameter to high energy nucleon electromagnetic form factor data. Nevertheless, it appears likely that quantitative predictions of the deuteron and "singlet deuteron" binding energies and low energy properties will continue to require adjustment of sensitive, and ambiguous, phenomenological parameters.

In contrast, a straightforward application of the covariant singular core model[1] to the $NN\pi$ system predicts both binding energies within one percent of their empirical values.[2] The three constants required for each calculation are obtained directly from experiment with no adjustment of parameters. The

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two-body models used as input in the calculation use the empirical fact that at high energy (i.e., in the particle production region) the two-body elastic partial wave amplitudes seem to be well represented by a constant logarithmic derivative of the wave function at a fixed radius. Theoretically this is what one would expect if this radius represents the transition between the internal quark dynamics and the peripheral behavior of separated hadrons (systems of bound quarks). Alternatively, we could view this radius as that of the diffractive disc required in the elastic channel by the opening and persistence of particle production channels at high energy.

The dynamics of covariant three-body calculations approaches the simplicity of non-relativistic Faddeev-type models if we require that we discuss the scattering of each pair in the coordinate system in which they remain in their own center-of-mass (zero momentum) system when the spectator particle recedes to infinity. We can then use free-particle wave functions right down to the geometrical limit of the core radii. Calling the square of the invariant four-momentum $P^2 = s$, the momentum of each particle in the distinguished pair k, and the momentum of the third particle $(m/(m_\beta + m\ ))p$, with $m = \Sigma_\alpha m_\alpha$, this imposes the kinematic restraint

$$\left(k^2 + m_\beta^2\right)^{\frac{1}{2}} + \left(k^2 + m_\gamma^2\right)^{\frac{1}{2}} = \left(s + (mp/(m_\beta + m_\gamma))^2\right)^{\frac{1}{2}} - \left(m_\alpha^2 + (mp/(m_\beta + m_\gamma))^2\right)^{\frac{1}{2}} .$$

Since the energy of the scattering pair is bounded by $s^{\frac{1}{2}} - m_\alpha$, to calculate the nuclear force at threshold ($s^{\frac{1}{2}} \sim 2M$), we need to extrapolate the two-nucleon input a pion mass below threshold. Since the three-body equations require the two-body logarithmic derivatives at the core radii to be meromorphic functions of k^2 in order to preserve the correct analytic structure, we need only know nucleon-nucleon scattering above pion production threshold, where empirically the logarithmic derivatives are constant if the core radius is correctly chosen. The P_{11} amplitude is needed in the narrow range near the nucleon pole $-\mu^2 \leq k^2_{\pi N} \leq -\mu^2(1-\mu^2/4M^2)$. So far as we can see, the states other than $^1S_0$ (which drives $^3S_1$) and $^3S_1$ (which drives $^1S_0$) and P_{11} will be much less important because of centrifugal barriers and will work in a direction to remove the remaining MeV or so discrepancy with experiment.

If this nuclear force calculation were the only result, we might, as one critic has remarked, have obtained the right result for the wrong reason. But as Brayshaw reported at Laval,[1] using the ϵ_0 and the ρ as two-body input for the 3π system, gives the 0^- I=1 pion as a bound state at the right mass, and 1^-, I=0 as a resonance at the position of the ω. More recently he has shown that both the A_2 and the A_1 are given, with correct experimental properties, using the same input. Perhaps even more significant is the fact that the calculations do not allow other low-lying bound states or resonances to appear in these channels. I think the time has come to take this way of doing relativistic particle mechanics seriously.

Although the singular cores are a very natural starting point from the perspective of the quark model, the free-particle input and the kinematic restrictions persist if the cores are allowed to shrink to zero, and the cutoff provided instead by a unitary correction taking account of the opening of inelastic channels at high energy. I have no quantitative calculations to report for this approach, but have taken it far enough to believe that it is possible to consistently treat the π as a bound state of $N\bar{N}$, $N\bar{N}N\bar{N}$, ... together with the nucleon as a bound state of N, $N\bar{N}N$, $N\bar{N}N\bar{N}N$, ... in such a way as to preserve crossing to the order considered. Replacing the N by the electron and the π by the photon should generate the <u>renormalized</u> QED perturbation series in the same way, and will provide a unitary way to introduce hadronic corrections to QED at a level where they are coming over the experimental horizon.

Whether the quark interpretation, or the vague bootstrap ideas indicated in the last paragraph turn out to be better approximations, I have a real hope that we are now on the verge of turning the deuteron problem into the "Bohr Atom" of strong interaction physics.

References

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2. D. D. Brayshaw and H. Pierre Noyes, Phys. Rev. Letters (June 23, 1975).