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Edited by

Takeshi Kodama

Centro Brasileiro de Pesquisas Físicas

Yogiro Hama

Universidade de São Paulo

Kai Cheong Chung

Centro Brasileiro de Pesquisas Físicas

Sergio J. B. Duarte

Centro Brasileiro de Pesquisas Físicas

M. Carolina Nemes

Universidade de São Paulo

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QUARKS IN HADRONS AND NUCLEI

J. E. Villate

CFNUL-GTAE
Av. Prof. Gama Pinto, 2
1699 Lisboa Codex, Portugal

ABSTRACT

Results for the masses of hadrons using a quark model with confinement and chiral symmetry are shown. A one-dimensional simple model is also used to estimate the effects of the quark substructure of nucleons in nuclear structure.

The simple picture of a hadron as a bound system of either three quarks (baryon) or a quark and an antiquark (meson), is very successful in explaining hadron spectroscopy. Even without knowing the details of the dynamics of quarks –the so called naive quark model– one can obtain a large amount of information in good agreement with the observed data –quantum numbers, magnetic moments and mass formulas.

Some dynamical quark models have been developed, in which quarks and antiquarks interact through a two-body potential, inspired on QCD [1]. These phenomenological models are very successful in explaining hadron spectroscopy. However, they are non-relativistic and assume certain large *constituent* quark masses, different from the *current* quark masses of QCD. On the other hand, they do not incorporate an important ingredient in hadron physics: the approximate chiral symmetry and its spontaneous breakdown. As a consequence they fail to explain why the mass of the pion is one order of magnitude smaller than baryon masses.

The model introduced by Le Yaouanc, Oliver, Pène and Raynal [2], considers relativistic current quarks and a phenomenological potential that both confines quarks (antiquarks) and provides a dynamical mechanism for spontaneously breaking the chiral symmetry. The Hamiltonian of the model is

$$H = \int d^3x \, [H_D(\mathrm{x}) + H_I(\mathrm{x})] \ , \tag{1}$$

where H_D is the *free* Dirac Hamiltonian density

$$H_D(\mathrm{x}) = \psi^\dagger(\mathrm{x}) \left(m\beta - i\boldsymbol{\alpha}\cdot\boldsymbol{\nabla}\right) \psi(\mathrm{x}) \ , \tag{2}$$

and H_I an instantaneous interaction term

$$H_I(\mathrm{x}) = \frac{1}{2}\int d^3y\, V(\mathrm{x}-\mathrm{y})\, \psi^\dagger(\mathrm{x})\frac{\lambda^a}{2}\psi(\mathrm{x})\, \psi^\dagger(\mathrm{y})\frac{\lambda^a}{2}\psi(\mathrm{y})\,. \tag{3}$$

Here λ^a are the Gell-Mann color matrices and $V(\mathrm{x}-\mathrm{y})$ a confining potential, for instance a potential linear or quadratic on $\mid \mathrm{x}-\mathrm{y} \mid$. If $H_I = 0$ the field operators ψ and $\psi^\dagger$ are those of the Dirac theory, which can be written in terms of creation and anihilation operators for *free* quarks and antiquarks, $b^\dagger$, $d^\dagger$, b and d.

If the interaction is now "switched on" the operators that create interacting quarks and antiquarks, ($\tilde{b}^\dagger$ and $\tilde{d}^\dagger$), are not the same as in the free case. They are defined by the condition that the vacuum energy be minimum. This *condensed* vacuum, which is a state with no quarks or antiquarks, when written in terms of free quark operators corresponds to a condensate of quark-antiquark scalar pairs. The Hamiltonian (2) is chirally invariant in the limit of massless quarks ($m \to 0$). However, the vacuum condensate is not invariant under chiral transformations and chiral symmetry is spontaneously broken [2)].

Mesonic wave functions and masses have been calculated by solving the Bethe-Salpeter equation in the case of a quadratic confining potential [3)]. In the baryon case we have recently solved the bound state equation for three quarks using a variational approximation [4)]. Some selected results are shown in table I.

TABLE I. Masses of some mesons, the nucleon and the delta. The potential is quadratic with a parameter K_o^3 given by $(4/3)^{1/3}K_0 = 290$ MeV. The quark masses used are $m_u = m_d = 0$, $m_c = 1362$ MeV. The model results are from Ref. 4 and experimental data from Ref. 5.

Hadron	J^{PC}	Theory (MeV)	Experiment (MeV)
η_c	0^{-+}	3096	2979
J/ψ	1^{--}	3097	3097
χ_{c_0}	0^{++}	3332	3415
χ_{c_1}	1^{++}	3343	3511
χ_{c_2}	2^{++}	3365	3556
D	0^-	1998	1869
D^*	1^-	2005	2007
D_1	1^+	2499	2424
D_2^*	2^+	2552	2459
N	$1/2^+$	1378	939
Δ	$3/2^+$	1612	1232

By adjusting just one parameter for the confining potential and the current quark masses, a good description of the meson spectrum is obtained. In table I the masses of the up and down quarks were taken to be zero $m = 0$; in fact the results do not change much if m is between 0 and 10 MeV. However, the pion mass is very sensitive to m, and it becomes zero for $m = 0$ [3]. Choosing an appropriate value of m within 0 and 10 MeV gives a pion mass in excellent agreement with experiment. The masses of the nucleon and delta are approximately 400 MeV too high, because coupling of baryons to mesons has not been considered. The encouraging result is that the $N - \Delta$ mass splitting is approximately correct.

In the case of several hadrons, as in the nucleus, the problem of obtaining the quark state of the bound system becomes intractable. One may then use the quark state of the nucleon to do a folding of its internal structure with the nuclear structure obtained from an effective theory where nucleons are considered elementary. Hereafter we call this approach the *impulse approximation*. To see how this approximation works, let us consider a simple model that can be solved exactly at the quark level and compared to the impulse approximation results.

The model consists in a one dimensional system of non-relativistic quarks, with only one internal quantum number: color. These quarks are placed inside a box of length L that represents the nucleus. The model Hamiltonian is of the *non-linear Schrödinger* type

$$H = \int_0^L dx \left[\frac{1}{2m} \partial_x \phi_c^\dagger(x)\, \partial_x \phi_c(x) + \frac{g}{2} \phi_c^\dagger(x)\, \phi_d^\dagger(x)\, \phi_d(x)\, \phi_c(x) \right], \tag{4}$$

which corresponds to a system of fermions with a contact interaction of strength g. The color indices c and d should be summed over wherever they appear repeated. With an attractive interaction ($g < 0$), the lowest lying states are those with quarks clustered into color singlets with as many quarks per cluster as number of colors.

An effective theory where the clusters are regarded as elementary particles can be constructed and used to develop an impulse approximation[6]. Figure 1 shows the results for the momentum distribution $N(p)$ and the elastic form factor $F(q)$ of the deuteron. The effective theory was constructed in very good agreement with the energy spectrum and it also reproduces the momentum distribution very closely. However, in the case of the form factor it does not give the correct asymptotic behavior. This problem still remains even after the effect of Pauli exchange of quarks is included (*cluster approximation* in the figure). The reason is that both approximations assume the same state for a nucleon isolated or inside a nucleus. In this simple model the form factor shows the effect of the nuclear medium on the internal structure of nucleons.

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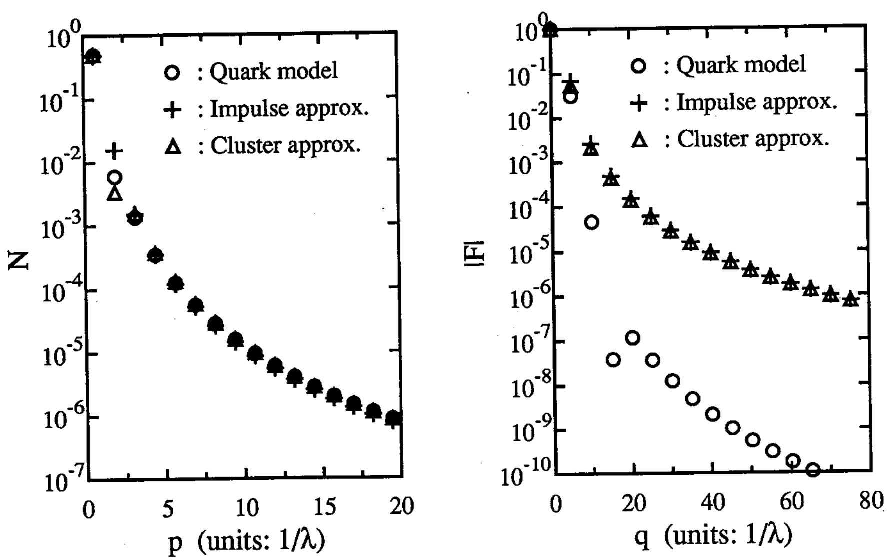

FIG. 1. The momentum distribution (left) and elastic form factor (right) of the deuteron, in the simple one-dimensional model. The parameter λ is the size of the free nucleon (from Ref 6).

DISCUSSION

J. Hill: Calculations by Vary indicate the deuteron to be a six-quark cluster about 5 % (if I remember correctly) of the time. Does your model shed any light on this matter ?

L. Wilets: A comment on the remark of Hill: Although it was once popular to consider the nucleus to consist of 3q and 6q clusters, such a division is too naiive. It is better to consider the nucleus to consist of 3q clusters, of pairs of interacting (distorted) 3q clusters, etc.

A. Gattone: I'm impressed with the spectroscopy you obtained for charmonium. Have you tried to calculate MI or EI transitions between your calculated states?

J. Villate: No, we have not calculated any transitions yet but in principle these can be done. The advantage of a quark model like this is that one can do a complete hadron spectroscopy study, as done in the Isgur-Karl model. On the other hand, by incorporating chiral symmetry one can also study the same observables calculated in chiral models (σ -model, Nambu-Jona-Lasinio, etc.).