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Keynote Address: New Directions in Intermediate-Energy Nuclear Physics

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NEW DIRECTIONS IN INTERMEDIATE-ENERGY NUCLEAR PHYSICS

By

G. E. Brown
Louis Rosen, Presiding

LASL COLLOQUIUM

August 21, 1979

Rosen: Good morning, Ladies and Gentlemen. It is my pleasure to introduce to you this morning Professor Gerald Edward Brown. I give you his full name so that there can be no confusion with another Jerry Brown whom some of you are acquainted with.

Our Gerry Brown was born in South Dakota. He received his bachelor's degree in physics from the University of Wisconsin, his doctorate from Yale in 1950, and his doctor of science degree from the University of Birmingham in England. At the University of Birmingham he worked with Professor R. E. Peierls, whom many of you know. Since then he has served as professor at the Nordic Institute of Theoretical Atomic Physics, and from 1964 to 1968 as Professor of Physics at Princeton University. In recent years he has divided his time between the State University of New York and the Nordic Institute for Atomic Physics in Copenhagen. He holds full professorships at both institutions.

I personally believe that Gerry Brown ranks among the three or four most influential nuclear physicists of our time. He has a gift for clarifying and simplifying very complex concepts and mechanisms, and he's done this in both nuclear and particle physics. He has been marvelously successful in simplifying various aspects of the unified nuclear model and models of giant dipole resonance. He has often found the key to puzzling nuclear problems such as the importance of ρ-meson rescattering within nuclei. He has also contributed to a new version of the quark model.

Gerry's taste in science is not only patrician but wide-ranging. For example, he has advanced the theory of nucleon-nucleon forces which so many of us here are interested in, from the dispersion point of view, and also our understanding of various astrophysical phenomena such as neutron stars. In nuclear astrophysics he has been working with Hans Bethe. Next spring, he will be Group Leader on Nuclear Astrophysics at the Institute for Theoretical Physics in Santa Barbara, California.

His book on unified theory of nuclear models, although not monumental in size, contains beautifully clear descriptions of important technical details, as well as overall concepts. This book appears to be headed to become a classic; it is already in its third edition. Professor Brown is a supervisory editor of *Nuclear Physics*, cofounder of *Physics Letters* and *Physics Reports*, a fellow of the Royal Danish Academy, and also of the U.S. National Academy of Science.

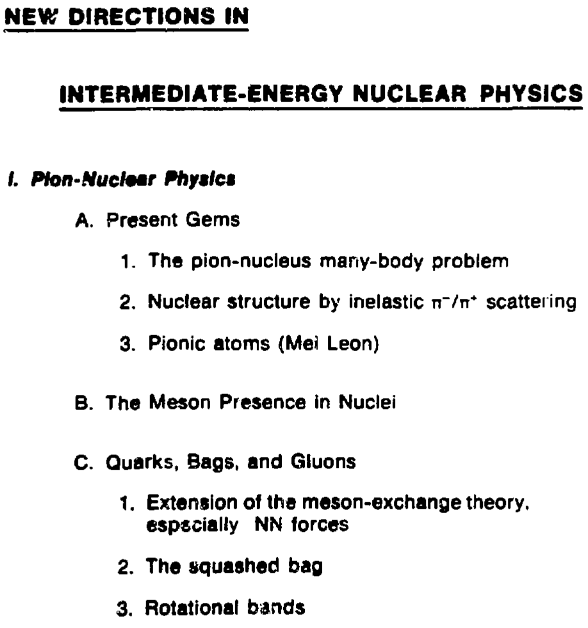
It is indeed a privilege to welcome Gerry Brown as our colloquium speaker this morning and also as the keynote speaker for the nuclear physics portion of our Program Options Workshop. His topic is "New Directions in Intermediate-Energy Nuclear Physics." Professor Brown.

Brown: Thank you, Louis. As Aldous Huxley said, "Flattery will get you nowhere, but it will get me here." I think that the introduction is a hard act to follow and the colloquium will just be going downhill after the initial play. Now today I want to talk about future directions in intermediate-energy nuclear physics, but I think in order to speak meaningfully about the future directions, one should look at some of what has happened and what I consider to be important in recent years in the past. So if I could have the first transparency, please? (See Fig. 1.)

In any case, in the outline I wish to cover first what I consider to be some gems of the present, some gems of what has been discovered in recent years. In order to have a manageable subject, rather than talking about all of the intermediate-energy physics, I want to talk about pion physics — in other words, pion-nuclear physics and the pion as it's connected with the meson presence in nuclei.

Now, there are many other topics in intermediate-energy physics and there are at least a dozen panels which will be discussing these for the next two weeks. It certainly would be impossible for me to even give an overview of all of these. So, with respect to pion-nuclear physics, I have chosen three particular topics. In order to have lots of pions one needs a good mousetrap. Other mousetraps are in TRIUMF and in SIN in Europe. I'm going to concentrate particularly on things which have been discovered here.

These are the present gems, and I shall pick out three of them. I wish to discuss the pion-nucleus many-body problem, nuclear structure by inelastic π^-, and π^+ scattering and also pionic atoms, to which I've added Mel Leon's name. Mostly I won't add names because the groups are rather large and people here know more or less who has been doing the work. I want to talk briefly about the meson presence in nuclei, which was one of the main reasons for building LAMPF and for doing intermediate-energy physics. This is all in the past or present, very much in the present, in fact. And I want to talk then about what I consider to be the near future. Of course the far future is more difficult to talk about because it's hard to discuss what will be unexpected in the far future, or it wouldn't be unexpected.



NEW DIRECTIONS IN

INTERMEDIATE-ENERGY NUCLEAR PHYSICS

I. Pion-Nuclear Physics

A. Present Gems
  1. The pion-nucleus many-body problem
  2. Nuclear structure by inelastic π^-/π^+ scattering
  3. Pionic atoms (Mel Leon)

B. The Meson Presence in Nuclei

C. Quarks, Bags, and Gluons
  1. Extension of the meson-exchange theory, especially NN forces
  2. The squashed bag
  3. Rotational bands

Fig. 1.

The next transparency (Fig. 2) shows important experiments of π^+ scattering on lead. I made this slide a long time ago before there were experimental errors on these plates. Things have not changed very much since then. These are 50-Mev π^+ scattering on lead with the Kisslinger model, the lowest-order optical model — that is, just taking scattering

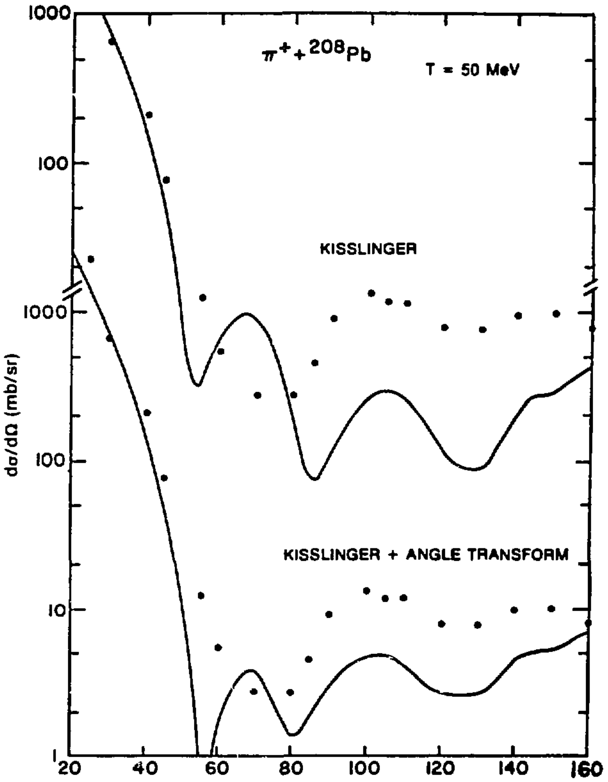


Fig. 2.
Elastic scattering of π^+ from ^{208}Pb. The points represent preliminary LAMPF data.

amplitudes in lowest order in the density. Now the point that I consider very important here is that in the low-angle region between 40 and 60 MeV, the drop in the theoretical curve comes about because of Coulomb-nuclear interference: the Coulomb interaction is repulsive for π^+ mesons, the nuclear interaction is attractive. The nuclear interaction in the Kisslinger description is really just much too large; the interference — this is a logarithmic plot — drops the curve nearly a factor of 10 just before the first diffraction minimum. Just the small-angle region is the one that is simplest to work with theoretically and depends least on a lot of details; this transparency (Fig. 2) indicates — and the extent of this was somewhat a surprise — that the pion-nuclear interaction at low energies is really very weak compared with a first-order description. In fact, the first-order description would predict about 1 part in 10^4 for the probability of a pion going through the center of the lead nucleus, and the experiments show that it's more like 1 part in a 100 or 3 parts in a 100.

The next transparency (Fig. 3) shows the same experiments; the theoretical curve here is where short-range correlations have been put in. The short-range correlations here are the Lorentz-Lorenz correction, which is completely analogous to the Lorentz-Lorenz correction that one has in electrodynamics, first discovered in approximately 1900.

In the next transparency (Fig. 4) I want to show what I would call a general picture of the pion nucleus many-body problem. What is envisaged in the lowest order optical model potential is that the pion comes into a nucleus and then it hits one or two or three or more nucleons and goes out. If we solve the Schrödinger equation with the optical model potential, this amounts to summing the multiple scattering. This is the Kisslinger potential. Now in fact, however, nucleons in the nucleus can interact through the exchange of many other particles than just the pion. And it's a vast oversimplification to consider the pion-nucleus scattering as involving only intermediate pions. Of course a pion has to come in and a pion has to come out, if that's what the experiment is looking for. But once the pion has been absorbed, the nucleons in the nucleus can exchange other particles, and this exchange of other particles is carried on under somewhat changed conditions than in the ordinary nucleon-nucleon force because a certain amount of energy has been put into the nucleus.

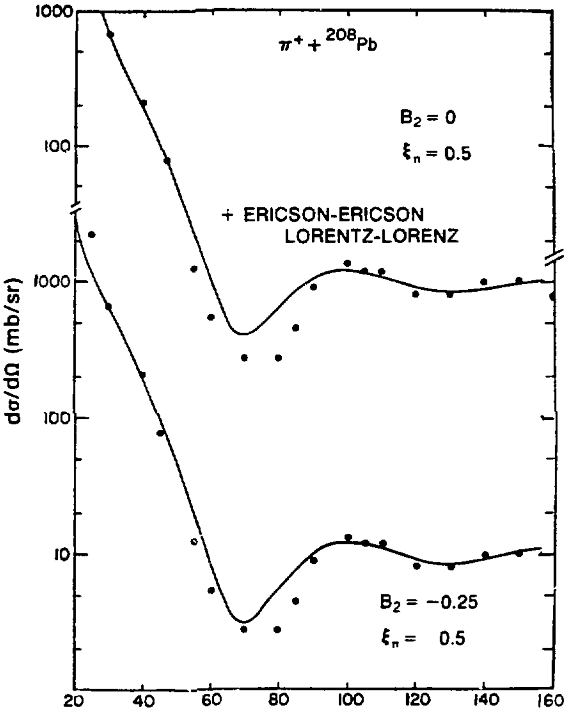
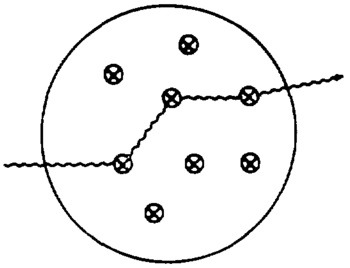


Fig. 3.
Elastic scattering of π^+ from ${}^{208}Pb$. The quantities B_2 and ξ_π are defined in Brown, Jennings, and Rostokin, Phys. Reports. Briefly, $B_2 = 0$ means that the classical Ericson-Ericson Lorentz-Lorenz correction has been made; $B_2 = -0.25$ means that 75% of the effect has been put in; ξ_π is a parameter in the angle transformation. Recent and better fits are available in preprint form from the Michigan State group (Carr, McManus, and Stricker), who use a considerably larger EELL correction.

The amount of energy that the pion carries in, if it is 200 or 300 MeV or, as in the case I've been talking about, 50 MeV, is rather small compared with the masses of the particles being exchanged. So the nucleons in the nucleus will interact through the exchange of the other particles; in fact, at the lower energies the net result of adding up these other interchanges seems to be to weaken the interaction that would come about from multiple scattering of only pions. How can the multiple scattering be weakened? It can be weakened by quantum-mechanical effects; one must add these processes coherently and they come in with opposite signs.

P-WAVE OPTICAL-MODEL POTENTIAL

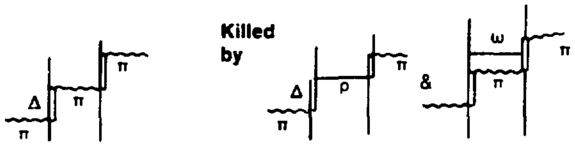
$$2\, m_\pi\, v_{opt} = 4\pi\vec{\nabla} \cdot (c_0\rho(r) + C_0\rho^2) \cdot \vec{\nabla}$$



Solving the Schrödinger Equation with v_{opt} ~ to summing the multiple scattering. Kisslinger potential.

Nuclear interaction at low energies seems much weaker.

Explanation



EELL - Many-body problem.

Fig. 4.
The optical-model potential. A microscopic description of the double scattering is given below.

Here I've drawn at the bottom of the figure a detail of the process where the pion excites virtually an isobar, a state 300 MeV above the nucleon, and then the isobar deexcites with the pion going across. This tends to be killed off by processes in which virtual ρ-mesons are exchanged and any number of ω-mesons. The ω-meson establishes the repulsive core — the repulsive short-range part of the nucleon-nucleon interaction — and keeps the two nucleons apart, so this latter term is completely equivalent to the old Lorentz-Lorenz correction as formulated in electrodynamics.

So the multiple scattering of the pion at low energies is killed off by these other processes which could be called short-range correlations. The problem of short-range correlations is one which has been around in nuclear physics for a long time. There are very few definite indications of them, and I believe that in the pion game the fact that the nuclear interaction has been weakened so much by the other processes coming in is one of the best indications of their presence.

The ρ- and ω-exchange lead to short-range interactions.

$$r \sim \hbar/m_{\rho,\omega}c \sim 0\ .$$

Can be incorporated by changing

$$4\pi\, c_0\, \rho(r) \rightarrow \frac{4\pi\, c_0\, \rho(r)}{1 + (4\pi/3)\, c_0\, \rho(r)}$$

R. Seki: important $\rho(\underline{r}) \cong 0.8\ \rho_{n.m.}$

Can compensate by choosing

$$\hat{c}_0 \simeq \frac{c_0}{1 + (4\pi/3)\, c_0\, (0.4)}$$ & leaving out correlations.

$$\cong c_0/1.4$$

$\therefore c_0 = 0.25$ corresponds to $\hat{c}_0 = 0.175$

c_0 should follow from π-N scattering.

CONCLUSION: Short-range repulsive interactions between isobars and nucleons.

Pion condensation → from $\rho_{n.m.}$ to ~ $2\ \rho_{n.m.}$

Fig. 5.
Short-range correlations in the optical model.

The way one discusses this is to introduce the lowest-order optical model potential which includes just the pion, and then modify it by the Lorentz-Lorenz correction to an expression as shown (Fig. 5). Seki has made an analysis of the low-energy scattering and of pionic atoms, and finds that the important densities are roughly 0.8 times nuclear matter density, i.e., 0.8 times central density, which is rather large. In the units I'm using it means that ρ in the denominator is roughly 0.4 and that the short-range correlation could, in fact, be renormalized out by choosing a different coupling constant, dividing by 1.4. Thus a smaller c_0 will give an essentially equivalent description of the process when used in the lowest order optical potential.

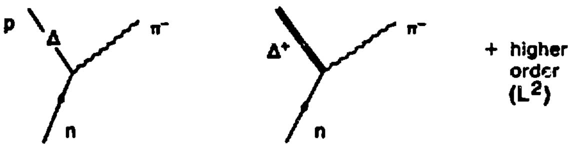
This means that when we use an optical model potential of this type, if we consider it to be phenomenological, then whether we use one form or the other will be immaterial in obtaining a fit. We have to put in theoretical information if we evaluate c_0 by starting from the forward-scattering pion-nucleon amplitude, and then build up the optical model from that definite value for c_0. In order to fit the data in that case, we must put in this denominator, bringing in an additional ρ. Alternatively, we could just consider this to be an exercise in fitting the experiment, but that's not to my taste; so I would say that if we take the c_0 from phase-shift analyses, then we need the effects of short-range correlations, and the low-energy pion-nucleus scattering work here has been a good indication of this.

So my conclusion is that there are short-range repulsive interactions between nucleons and nucleons and isobars, since in this case isobars come into play. Short-range correlations have many important effects. One of them is that pion condensation, a new form of nuclear matter, is predicted to occur at something like two times nuclear matter density and not at nuclear matter density, as would be the case if there weren't these short-range correlations between nucleon and isobar.

Now what is pion condensation? (See Fig. 6.) It's a new form of dense matter which is expected to be found and probably has been found at something like twice nuclear matter density. The idea of pion condensation is quite simple. Let me here go to as dense neutron matter as one would find in neutron stars. In that case a neutron will decay into a proton and a π^- meson. In general it won't decay because that's not energetically possible, but let's assume that we have neutrons splitting up into protons and π^-'s and maybe into isobars and π^-'s, too. If enough neutrons split up into π^-'s, which are in the same momentum state, then the matrix element for the pions to interact with protons and neutrons is built up by a factor of $\sqrt{N_\pi}$, boson factor, the same sort of factor that makes lasers go in the case of photons. So this means that the interaction is built up, and soon (if matter is dense enough and there are enough pions in this particular state), the attraction which results from this interaction is greater than the energy of the pion which has to be formed.

PION CONDENSATES —

A NEW FORM OF DENSE MATTER



Proton (or Δ^+) is created so a neutron can interact with p via π^--mesons. By macroscopically filling the π^--state, matrix element is built up by $\sqrt{N_\pi}$. At high densities, attractive interaction is larger than E_π.

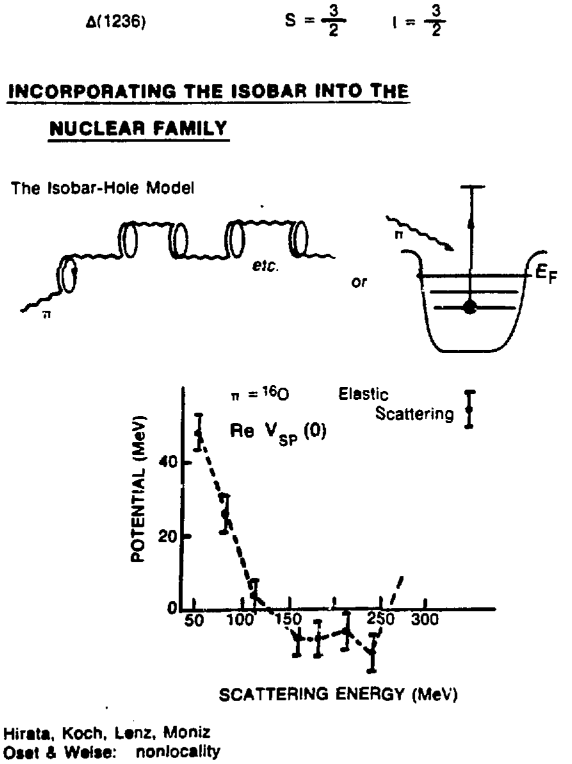
These densities are reached in neutron stars & in the gravitational collapse of stars.

Fig. 6.
Pion condensates.

At this stage it pays to create more pions because we gain more attraction than the energy of the pion that we have to pay. And this would continue except for higher order pion-pion interactions. High-enough densities are reached in neutron stars and they are reached in the gravitational collapse of stars, so at least in astrophysics these processes are important. It's not clear that they're important in intermediate energy or in heavy-ion physics. These matters are being discussed.

The pion condensate has spectacular effects in the cooling of neutron stars, because in the cooling of neutron stars standard processes have to involve two particles whereas the pions that are running around can freely β-decay, and it turns out that cooling of neutron stars in the presence of a pion condensate goes about a million times faster than through standard mechanisms. Recently the Einstein Observatory has pinned down the surface temperatures of neutron stars to something like 10^6 K, and it's just quite difficult to get them that low by standard cooling scenarios so that the presence of pion condensates in neutron stars seems to me, if not established, to be highly probable. There are connections here in the sense that the densities in which the pion condensates come are controlled by the short-range correlations between nucleons and those between nucleons and isobars, so it's amusing that one can perform experiments here at LAMPF which bear on the densities at which pion condensates are formed in completely different systems.

I want to discuss a little more how the isobar enters into pion scattering. If a pion comes in, a nucleon will be lifted up into an isobar and this can be thought of as an isobar-particle nucleon-hole interaction. People at MIT have made an isobar particle nucleon-hole picture out of this so that the description is much like that in collective states in nuclei; they have a good description of elastic scattering of pions (Fig. 7). However, they have to put a couple of parameters into this description, and one of the parameters is the interaction of the isobar with the nucleus, which in this particular case is the real part of the potential energy of the interaction of the isobar with the nucleons in the nucleus. The MIT group finds that in order to fit the data, this real part must be rather repulsive at low energies, which I've been talking about, but as we move up in energies into the isobar region, ~180 MeV, it must become quite attractive.



$\Delta(1236)$ $S = \frac{3}{2}$ $I = \frac{3}{2}$

INCORPORATING THE ISOBAR INTO THE NUCLEAR FAMILY

The Isobar-Hole Model

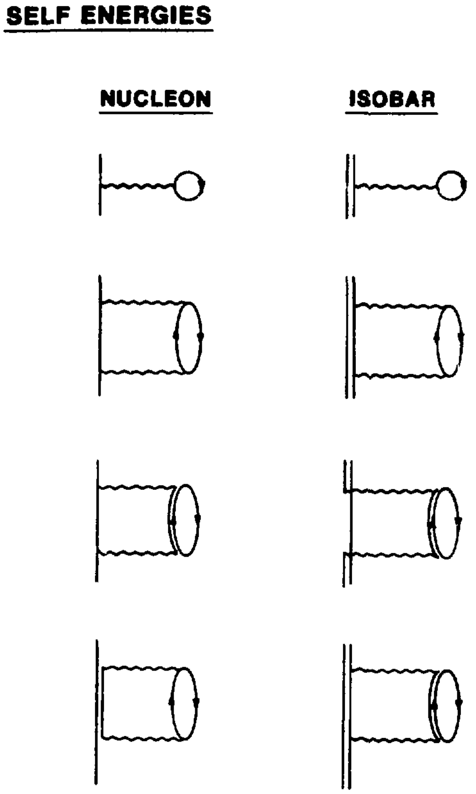
Hirata, Koch, Lenz, Moniz
Oset & Weise: nonlocality

Fig. 7.
Shell-model theory of the isobar.

This change in potential energy is really pretty dramatic. It's not completely clear that all of this is really a change in the real part of the isobar energy; some of it according to Oset and Weise can come from nonlocality of the interaction. This needs to be sorted out, but I would point out that this poses an interesting question and we are being forced more and more to adopt the isobar into nuclear physics as just another member of the family. It's a member that does not exist in nuclei as they sit around, except as a virtual mixture. In order to form an isobar really, one has to put in a certain amount of energy into the nucleus.

Once we adopt the fact that the isobar must be incorporated into the nuclear family, then we see that when we want to calculate self-energies we have to begin calculating self-energies of the isobar in the same way as we calculated self-energies of the nucleon. The double line in the transparency (Fig. 8) means an isobar, the single line a nucleon. We had to include the isobar in intermediate states. When we calculate energies of the isobar we have to include the nucleon as an intermediate state and we have the processes shown where the isobar actually goes down in intermediate-state energy. In any case, if one writes down all of these processes to second order and adopts coupling constants of the isobar and the nucleon from the constituent quark model, then one finds that the self-energy one would expect from the nucleon and the self-energy one would expect from the isobar are about equal; there is a symmetry there dictated — not dictated, because it's not true — but predicted by the constituent quark model. This is roughly true because the isobaric excitation in nuclei does come at about the same energy as in free space, which means that one gains about as much potential energy from the isobar interaction with the nucleus as one loses through pulling out a nucleon, but it's probably not true in detail, and in particular there are quite interesting suggestions.

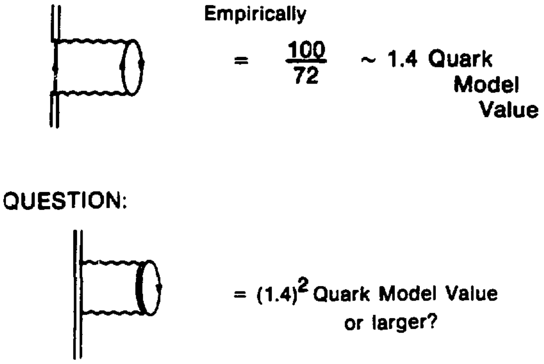
One is that we know empirically, from fits to pion-nucleon scattering where the coupling constant is equal to that in the old Chew-Low model, that the square of the coupling between isobar and nucleon in reality is about 1.4 times the quark model value. That is, the quark model is not literally true. The question is, would an interaction which involves two isobars be much larger than that given by the quark model? — for example, 1.4 squared times larger (because I claim a factor of 1.4 each time an isobar is



CONSTITUENT QUARK MODEL

ISOBAR SELF-ENERGIES = NUCLEON ONES.

Fig. 8.
Nucleon and isobar self-energies in the nuclear many-body problem.



Empirically

$= \frac{100}{72} \sim 1.4$ Quark Model Value

QUESTION:

$= (1.4)^2$ Quark Model Value or larger?

Would explain energy dependence of isobar-nucleus potential.

Pionic interactions inside the nucleus may be a lot stronger than predicted by quark model.

Fig. 9.
Comparison of empirical $\pi N\Delta$ coupling constants with those from the constituent quark model.

introduced, not from any theory but only as a suggestion)? (See Fig. 9.) Well, if that's true this would give rise to a growing attraction in the potential with increasing energy in the case of the isobar because of coming closer and closer in energy to this intermediate state, and it could explain some of the energy dependence in the isobar-nucleus potential. But the main suggestion that I wish to raise is that pionic interaction inside the nucleus may be a lot stronger than predicted by the quark model. Preliminary indications are, or there are some preliminary indications (and the only way you can investigate points like this is by putting the isobars into nuclei), that this is so. This is the sort of connection of deltas with nuclear physics that I want to emphasize.

Now we've come to a pretty good understanding of the role that the Δ-isobar plays in the nucleon-nucleon interaction, and in particular we come to the understanding that the intermediate-range attraction, which goes very much like in the old Yukawa theory through the exchange of essentially spin-zero, isospin-zero objects (and that gives the attractive interaction between two nucleons), is made up out of isobar degrees of freedom (Fig. 10). If one puts together virtual isobars, most of this intermediate-range attraction, more than three-fourths, comes from this process. So the understanding of the isobar problem bears on the interactions in the nucleus, and in particular I at least am convinced that the problems one has with nuclear matter theory will only be resolved when one has built the virtual isobars explicitly into the nucleon-nucleon force, treating the nuclear many-body problem with both nucleons and isobars. We've had a tremendous amount of work on the nucleon-nucleon interaction in nuclei and on the binding energy in nuclei, but rather little has been done putting in the isobar degrees of freedom explicitly.

Now I want to deal quickly with pions as probes. In one sense the pion adds just one additional probe

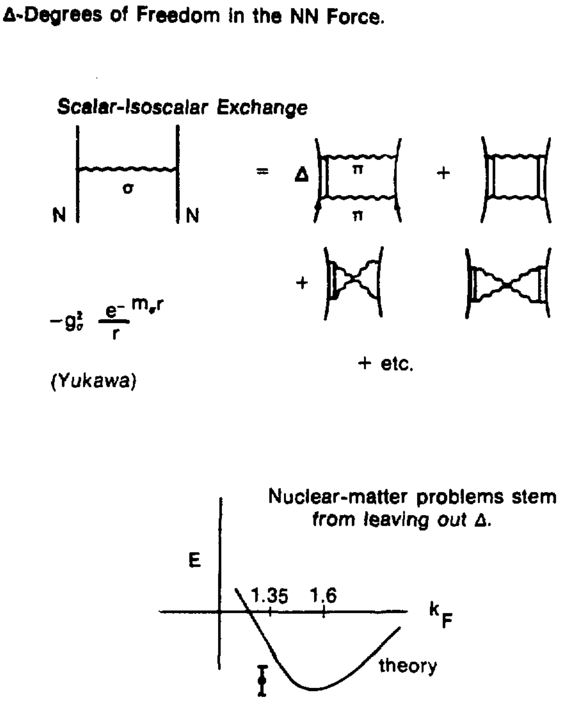


Fig. 10.
Role played by the Δ degrees of freedom in the nucleon-nucleon force.

to the many probes we have in nuclear physics, but in another sense it has its own special properties, and a particular example that I brought out is excitation by inelastic scattering in ^{18}O, going from the ground state to the 2^+ excited state. If ^{18}O consisted of only two neutrons outside of a closed shell, which would be the naive shell-model view of the nucleus, then because π^-'s in the 3-3 resonance region interact much more strongly with neutrons than π^+'s, one would predict a ratio of 9 for π^- to π^+ scattering (see Fig. 11). In fact, the experimental ratio is closer to 2, and this means that there are major modifications. We've known for a long time that in ^{18}O the ground state is not completely spherical, that there is a coexistence of really highly deformed states nearby, and I would point out that these highly deformed states will stick out in space well beyond the spherical state and that a lot of the inelastic excitation will go through, hitting the ends of these highly deformed states, in which case the pions are relatively undistorted.

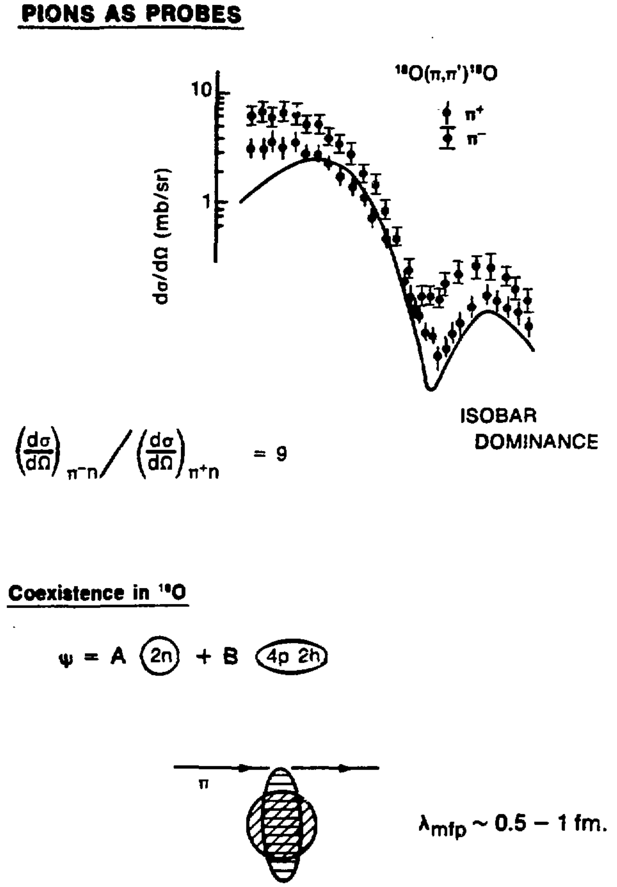
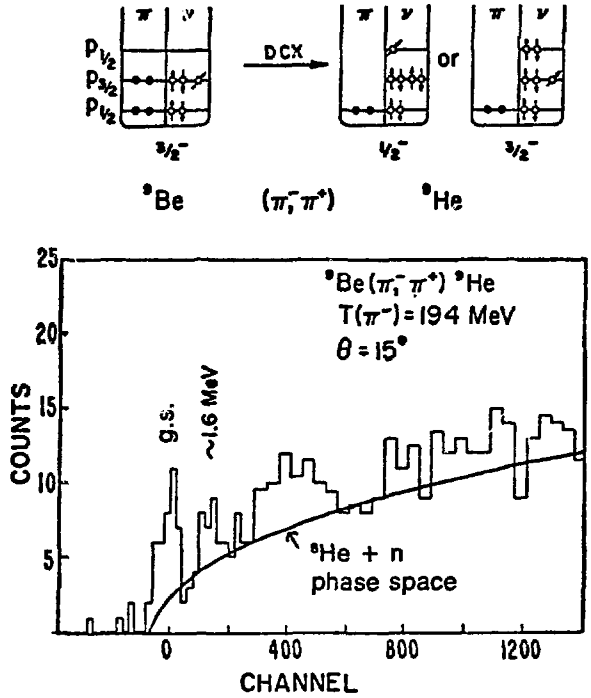


Fig. 11.
Use of pions as probes in investigating nuclear structure. In the lower part of the figure the shapes of spherical and core-deformed pieces (prefixed by A and B in ψ) of the wave function are sketched.

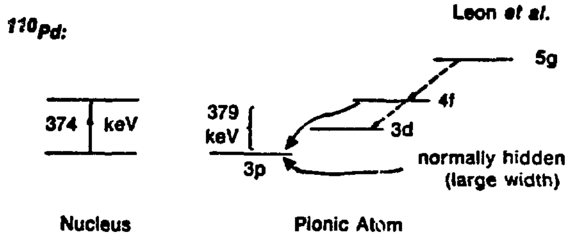
This is a rather quick trip through, and I'll make it even quicker because of lack of time. I'll show the slide of Seth's experiments on helium (Fig. 12); the envelope (under my door last night) had only Seth's name on it, but of course I refer to the whole group. And I'll whip through the dynamics of pionic atoms or I won't get to what I want to say about the future; I think that one should put Mel Leon's name down because he's pursued the whole business of the dynamics of pionic atoms in a single-minded way (see Fig. 13). Recently Dubach, Moniz, and Nixon have pointed out that the situation is really much



Seth *et al.* (Aug. 1979)

Fig. 12.
Formation of new nuclei in double charge exchange.

DYNAMICS OF PIONIC ATOMS



Pion-nucleus quadrupole interaction admixes a little

$\Phi(3p)\ \chi_N(2^+)$

with $\Phi(4f)\ \chi_N(0)$. Admixed 3p level increases attenuation of 4f level.

Admixture depends sensitively on energy denominator

$E(4f;\ 0) - E(3p;\ 2^+)$.

Strong interaction shift (pion nucleus) in 3p-state found repulsive, as predicted by Ericson.

See "Dynamical Polarization in Pionic Atoms," by Dubach, Moniz, and Nixon.

Fig. 13.
Dynamics of pionic atoms.

more complicated than people had thought, but they also point out that there's a possibility of learning much more about nuclear structure. This means that this particular area will continue to grow; it's not just going to stay where it is. In particular, Leon and collaborators were able to show that the strong interaction shift in P-states changes from being attractive to repulsive, verifying this prediction here.

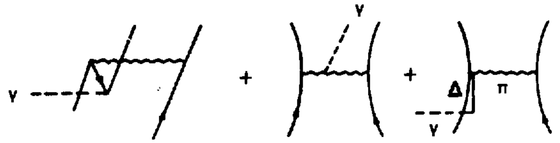
Next I want to talk about the meson presence in nuclei (Fig. 14). Here I'll go over to electromagnetic means. I think that one of the success stories in nuclear physics has been working out in detail what the exchange currents are. That is, if I send a gamma ray, real or virtual, into the nucleus, it need not tie on only to the nucleonic charge, but it may in particular catch mesons in midair. Or it may couple on to isobars, or it may detect the presence of virtual nucleon-antinucleon pairs in the nucleus.

Now one of the great advances in the theory of exchange currents came with the partially conserved axial current. Chiral symmetry 10 or 15 years ago was accepted just as the sort of empirical symmetry which seemed to give one a lot of guidelines in working out nuclear theory, and we were able to understand through it a lot of questions which I consider to be fairly deep; for example, "Why, although we have strong interaction physics, are three-body forces really pretty weak in nuclei compared with two-body forces?" The chiral game really taught us how to "single count"; before, the problem had always been that we could find plenty of processes, exchange-current processes like this, but we never knew when to stop. We had just masses and masses of them; the partially conserved axial-vector current (PCAC) told us how to do our bookkeeping.

Let us look, for example, at the electrodisintegration of the deuteron, where the electron hits the deuteron and the deuteron splits up into two objects of low relative energy, neutrons and protons coming off (Fig. 15). The impulse approximation in which the virtual gamma ray ties on simply to the nucleons predicts the dashed curve. The solid curve was the

THE MESON PRESENCE IN NUCLEI

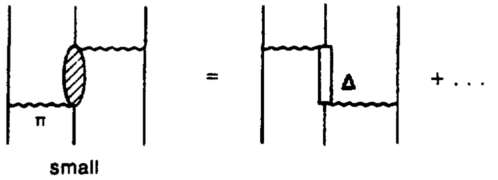
Exchange Currents



Important region is 0.5 – 1.5 fm.

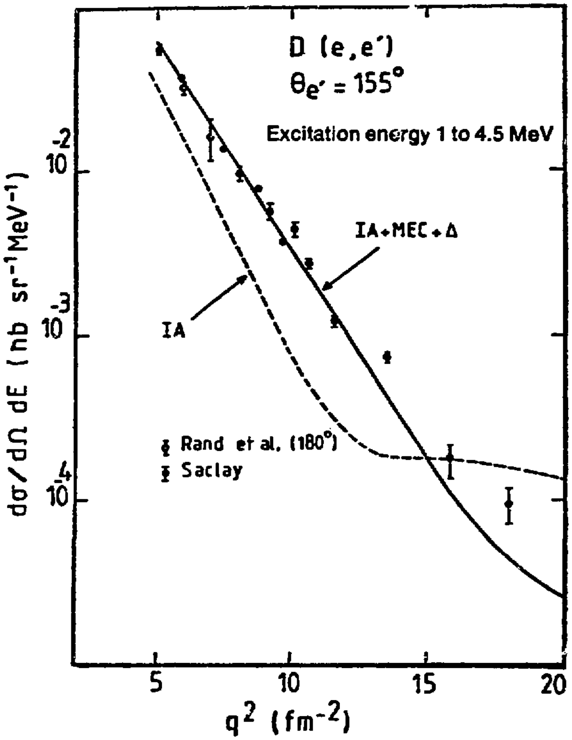
PCAC → single counting.

Relative lack of 3-body forces in nuclei.



Can be understood from PCAC.

Fig. 14.
Processes giving rise to exchange currents and three-body forces in nuclei.



Royer, Barreau, Barnheim, Jans, Morgenstern, Mougey, Tarnowski, Turck, Capitani, Frullani, DeSanetis, and Sick.

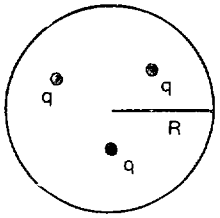
Fig. 15.
Electrodisintegration of the deuteron to states of low relative n-p energy by Royer et al. *(Saclay).*

theoretical calculation, and most of it a prediction which was well fulfilled through French measurements during the last year. So you see that in this particular case, because of the carefully controlled kinematics, the meson presence in the nucleus gives nearly a factor of 10 in the cross section, and the comparison with theory shows that we have this sort of process pretty well in hand. This is just one example, probably the most spectacular, but it is just one example out of many. Now this tells us that we have an understanding of the meson presence in nuclei from our description of pion exchange. All of these processes are connected in a way, as I showed in the figures before, with pion exchange, namely *nucleons exchange pions*. The range in configuration space that contributes to these exchange currents is something like 0.5 to 1.5 fm. We have quantitatively the understanding of the pion exchange. Therefore nuclear physicists, if they think about it, should be rather shocked to find bag models of nucleons with quarks where quark bag models are something like a fermi in radius. We really have to think seriously about what is the structure of nucleons because we have an old-fashioned description of nucleon-nucleon interactions which seems to work over quite a wide range from 0.5 fm on out, and this would be greatly modified if the internal structure of the nucleon were really large in extent.

Now I want to talk somewhat about bag models (Fig. 16) because I think that nuclear physics and particle physics will merge from, in the former case, the low-energy end, and in the latter case the high-energy end. They will merge in their description of the nucleon and of the delta. In particular the quark model gives a much simpler description of the delta as an elementary particle than we had before. To my mind there is no doubt that the delta is an elementary particle excited by the spin flip of quarks from

BAG MODELS

The MIT Bag



R ~ 1 fm

Vector current confined by

$$\gamma \cdot \mathbf{n} \quad q|_R = q|_R$$

Leads to $(\bar{q}\, \gamma \cdot \mathbf{n} \quad q)|_R = 0$.

$$\vec{A}_\mu = -i\, \bar{q}\, \gamma_5\, \gamma_\mu \; \frac{\vec{\tau}}{2} \quad q \qquad \theta(R - r)$$

$$\vec{A} \cdot \mathbf{n}\, |_R = -\, i\, \bar{q}\, \gamma_5 \; \frac{\vec{\tau}}{2} \quad q|_R \; .$$

Violates $\frac{\partial A_\mu}{\partial X_\mu} = 0$.

Fig. 16.
The MIT bag model.

"WITH APOLOGIES TO MAXWELL"

Ampere's Law

$$\nabla \times \mathcal{H} = \frac{1}{c}\, \mathbf{j} = \frac{1}{c}\, \rho\, \mathbf{v}$$

$$\nabla \cdot [\nabla \times \mathcal{H}] = 0 = \frac{1}{c}\, \nabla \cdot \mathbf{j}$$

-no continuity-

Maxwell: Add displacement current $\dot{D}$ to RHS

$$\nabla \times \mathcal{H} = \frac{1}{c}\, (\mathbf{j} + \dot{\mathbf{D}})$$

$$0 = \nabla \cdot \mathbf{j} + \nabla \cdot \dot{\mathbf{D}}$$

$$= \nabla \cdot \mathbf{j} + \dot{\rho} \qquad \text{O.K.}$$

For virtual pions close to the nucleon, can neglect m_π ir , e.g.,

$\frac{e^{-m_\pi r}}{r}$, so that $\frac{\partial A}{\partial X_\mu} = 0$.

Fig. 17.
Role of the displacement current in conservation of the vector current in electrodynamics.

the nucleon. So we have to understand these questions in order to meaningfully discuss the role of the delta in the nuclear many-body problem.

In the MIT bag model the vector current is confined by fiat (we cannot have colored currents escaping); a boundary condition is put on which leads to the vector current being zero at the radius of the bag. The problem comes, however, when one calculates the axial vector current, the sort of operator responsible for β-decay. When one goes back to quantum chromodynamics, the theory we all believe in these days, the quarks and gluons play a primary role but the currents also play a very basic role. If we construct the axial current out of only quarks, this axial current must necessarily in this model be restricted to be inside the bag because nothing can get outside. However, the normal component of the axial current at the bag surface, if use is made of the confining boundary condition, turns out not to be zero. This condition sets large and small components of the quark wave functions equal, so the normal component of the axial current is really about as large as it can be at the boundary. Therefore the continuity equation on the axial vector current, which is a strict operator equation in quantum chromodynamics, is violated about as much as it can be.

Everybody knows that this year is the hundredth anniversary of Einstein's birth, but very few people remember that it's the hundredth anniversary of Maxwell's death, and I want to point out what Maxwell did when confronted with Ampere's law. Ampere's law didn't work because if I take $\nabla \cdot \mathbf{J}$, then the right-hand side gives $\nabla \cdot [\nabla \times \mathbf{H}] = 0$. This is not a very good continuity equation on the ordinary electromagnetic vector current (Fig. 17). Maxwell added a displacement current, which at that time was kind of a mysterious object, to the equations. Having added the displacement current to Ampere's law one finds a perfectly good continuity equation on the vector current. I would claim that we have to do the same thing in the bag model, namely we have to add an additional axial current, and the additional axial current is conveniently furnished to us by the pion field. If I take chiral models with pions in I find that a pion does contribute to the axial current, so say that the axial current consists of the quarkish axial current inside the bag and it consists of the axial current coming from the pion outside the bag. Now if I then join the pion field outside of the bag in such a way as to make the axial current continuous across the bag surface, this determines the coupling strength of the pion field. And if I look at that field asymptotically (Fig. 18) and use the Goldberger-Treiman relation to connect the pion decay constant with the strong interaction constants, I find that this asymptotic pion field is just the usual Yukawa one with the usual coupling strengths.

THE CHIRAL BAG Rho

$$A_\mu = -i\bar{q}\gamma_5\gamma_\mu\frac{\vec{\tau}}{2}q\,\theta(R-r) + f_\pi D_\mu\vec{\phi}_\pi\theta(r-R)$$

$$D_\mu = \frac{1}{1+\frac{\phi_\pi^2}{f_\pi^2}}\partial_\mu$$

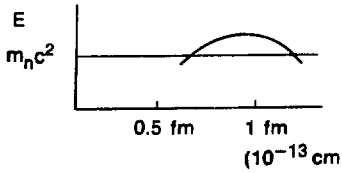
Asymptotic pion field is the usual Yukawa one with correct coupling constant.

HEDGEHOG SOLUTION Vento, Jun, Nyman, Rho

Fictitious nucleon 50% ↑ 50% ↓
(~ spherical shell model)

B.C. Continuity of axial current.

$$\gamma\cdot nq = \frac{1}{f_\pi}(\sigma + i\vec{\tau}\cdot\vec{\pi}\gamma_5)q$$



$$E = \frac{3(2.04)}{R} + \frac{4\pi}{3}R^3B + E_\pi$$

Fig. 18.
The chiral bag. In the bottom half of the figure, energies for the hedgehog (spherical) solution obtained this summer by Vento, Jun, Nyman, and Rho are sketched.

So this, to me, is a very compelling way to join the pion on to the bags; then the bags can communicate with each other, so if I bring a second nucleon up close it will interact through this pion field and I'll find the one-pion-exchange potential in the nucleon-nucleon force. Now, as I'll point out soon, the coupling of the pion field squashes the bag. The bag will no longer be spherical and this has important consequences. The pion field couples to the spin of the nucleon so it couples primarily at the poles and not at the equator, so the nucleon and isobar will be oblate squashed objects that are probably about twice as long as they are thick. That's our estimate. That's a very hard problem to solve, but this summer we did solve the problem after averaging the spin of the nucleon over angle so as to make a spherically symmetrical problem out of a problem that is intrinsically not spherically symmetrical, and using a chiral generalization of the MIT boundary condition to confine the quarks.

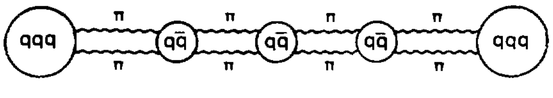
We then got a numerical solution to the classical problem of a bag, boundary conditions given by confinement of the vector current and continuity of the axial current, and an external nonlinear pion field. A bag constant has to be put in, a bag pressure, which is still introduced here in the phenomenological way, and then an energy that comes from the coupling of the pions externally to the bag as well as to the kinetic energy of the quarks; this is called the hedgehog solution because if you look at any angle the spin of the nucleon is coming at you.

There is more than one solution with the right energy. One is a big bag with a small meson cloud, the other one is a small bag with a big meson cloud; and at least from this theory one has the interesting possibility, which I don't really believe, that the nucleon exists in a big-bag mode when one at a time, but in a nucleus where it's hard to insert big bags they'll flip to a small-bag mode so that they can lower their kinetic energy and can benefit from attraction of different bags due to meson exchange. This is with the pion coupled. It is still a simplified model, but it is a model which should be for the nucleon what the spherical shell model was for the nucleus where we can actually calculate radii. Now they are not in fact probably the real radii, but the small bag would, once squashed, give pretty much the primordial $p_\perp$ which I asked Maurice Jacob about yesterday.

We can now go into flights of fancy which turn out not to be so fanciful because they map on to older dispersion theoretical formalisms, when we can construct the ρ-meson. Rho-meson exchange between two nucleons is shown in Fig. 19, with the basic fundamental ρ-meson being a small, compact, heavy quark-antiquark bag; the ρ-meson communicates with the nucleon through pions. The continuity of the axial current essentially says that the bags are porous to pions; $q\bar{q}$ pairs with quantum numbers change character going through the bag and look more like fundamental fields outside. A pion may not really be this, but at this phenomenological level, which is somewhere between nuclear physics and QCD, the chiral invariance of the theory tells us unambiguously that we have to handle them in this fashion. Then if we want to reconstruct the nucleon-nucleon interaction we have a long-range part which comes from pion exchange, an intermediate-range part which would come from two-pion exchange, a short-range repulsion which comes from three-pion exchange, and then at some distance which is not too well determined yet, this force will be modified by the fact that the bags merge (Fig. 20). Now this is very hard to see in nuclei because the strong-range repulsion will keep nucleons apart and they'll hardly ever get to the point where the bags merge. One cannot calculate, without correlations, the probability that two particles will come on top of each other. You have to realize that repulsions will keep nucleons apart.

I want to return to the squashed bag and the fact that the pion pressure is largest on the poles of the bag (Fig. 21). The pion field compresses the bag and deforms the bag. In fact, one of the most fundamental experiments that one could do would be to measure the deformation of the isobar. The spin of the nucleon is not large enough for the nucleon to have an intrinsic quadrupole moment, but the isobar will have a quadrupole moment, and one can measure this by measuring the angular distribution of the decay gamma ray with respect to the direction of the incoming pion. The isobar is wide and can be excited up to a particular energy, decaying to the same state at a different energy through emission of a gamma ray. Now this is a very tough experiment to do because it is a small effect with other very large effects that follow from low-energy theorems, but I would point out that it is probably one of the most fundamental experiments that one could do on LAMPF. At least limits could be put on the quadrupole moment that are very much better than present limits, which are practically nonexistent.

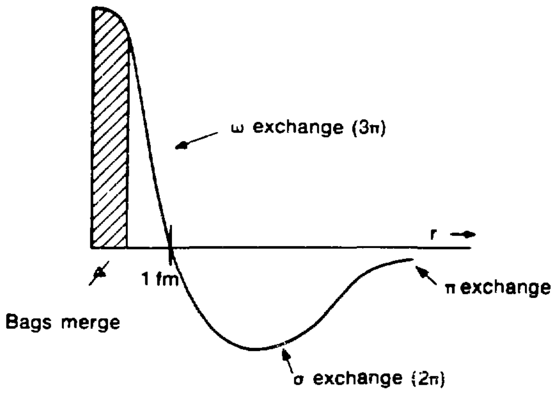
ρ-EXCHANGE



∴ pion cloud
bags porous to pions
usual boson exchange model until bags overlap.

Fig. 19.
Visualization in the chiral-bag model of the ρ-exchange component in the nucleon-nucleon force.

THE NUCLEON-NUCLEON INTERACTION



Dimension of Bags?

QCD has no dimensions.

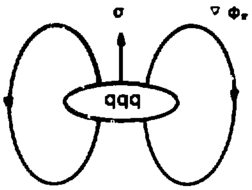
High energy

μ^- pair prod. / pN jets: $(p_\perp)_{int} \sim 600$ MeV (~ Λ of QCD)

∴ $R \sim \hbar/600$ MeV ~ 0.3 fm.

Fig. 20.
The nucleon-nucleon force, as modified by the bags merging at short distances. According to high-energy experiments, the intrinsic quark momentum, observed in hard μ-pair production and in p-p jets, is ~600 MeV, giving a bag radius of ~0.3 fm.

THE SQUASHED BAG



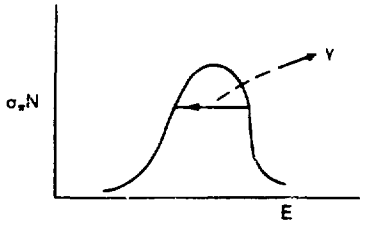
Pion field couples to spin

$\sigma_N \cdot \nabla \Phi_\pi$

1. Compresses bag
2. Deforms bag ($\delta \sim -0.5$)

Measure the deformation of the isobar Δ(1230)

(Garvey) J = 3/2.



$\pi + N \rightarrow \pi + N + \gamma$

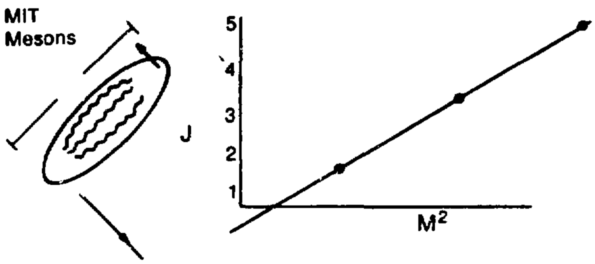
m = ±1/2 states populated

∡ dependence of γ.

Fig. 21.
The squashed bag, and the possibility of measuring the quadrupole moment of the Δ-isobar in LAMPF experiments.

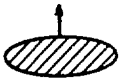
Once I have squashed bags and quark models I point out that the nucleon is in fact an I = 1/2 band head for a deformed K = 1/2 band, and the isobar will be an I = 3/2 band head for a deformed K = 3/2 band. That means if they rotate rapidly (and relativistically), they will form a rotational band which can be plotted as a Regge trajectory of J vs M². Now this is the same sort of thing that the MIT people have been using to discuss Regge trajectory of mesons where, in their theory, the inertia is carried almost completely by the color electromagnetic field. We see that to that colored electromagnetic field we have to add coupling of at least the pion field and possibly other mesons, so that the inertia as carried around will be greater. On the other hand the size is smaller, so hopefully (and this has not been worked out) their Regge trajectory will come out to be pretty much what it was before.

ROTATIONAL BANDS = REGGE TRAJECTORIES



Inertia carried by color lines.
Must add meson cloud.

BARYONS



Nucleon is I = 1/2, K = 1/2 band head

Isobar is band head for I = 3/2, K = 3/2.

Fig. 22.
Rotational bands and Regge trajectories.

I see, in what will be going on in the next 10 years, the conceptual framework of intermediate-energy nuclear physics coming together from the low-energy end, with the conceptual framework of particle physics coming down from the high-energy end (Fig. 22). I see a possibility for a reunification of physics, which has been badly split in the last couple of decades. We have to see our future in this way. I am really extremely enthusiastic and optimistic about being able to come together with the other part of the physics community through this kind of conceptual progress.

I would like to thank Mannque Rho, who participated in many of the developments I mentioned, especially in "the chiral bag."

Thank you.

* * *

Rosen: Although Gerry has to get a plane early this morning, he has time for a few questions.

QUESTION 1:

Do I understand correctly that, although you are not sure about the size and shapes of your bag, you definitely say that the MIT static model is wrong? And suppose that is the case, it would be very nice to come up with definite experimental proposals at this workshop together — not the kind of a tough experiment you discuss, this gamma-ray stuff — but it would be very good jointly at this workshop if we could come up with some experimental proposal.

ANSWER:

My *feeling* is that the MIT bag is wrong. However, when we got the numerical solution to the spherical bag problem, we had two solutions: one was a large bag with a small meson cloud, which looked just like the MIT model with a small cloud put on. The modifications actually improve somewhat their model, the value of g_A, which went up, as in the Adler-Weissberger relation, to 1.25. The other solution was a small bag with a large cloud. If I look at characteristics of the solution, mathematical characteristics, the MIT one in fact had better characteristics, so from our work I cannot dismiss the MIT bag. I'm talking from a gut feeling about sizes and primordial $p_\perp$, so I believe in the small bag. What I do know is that one has to enforce the chiral invariance for coupling the meson cloud in some way. But certainly there must be consequences of a large bag with a small cloud as compared with a small bag and a large cloud.

Are there other questions? Yes, Vernon Hughes.

QUESTION 2:

Are any of these viewpoints about mesons and deltas in nuclei which have been applied to some of the old problems like magnetic moments, exchange contributions, or hyperfine structure anomaly?

ANSWER:

I don't know about the hyperfine structure anomaly, but through the exchange corrections to magnet moments there's been a lot of work done and I think we have a fairly good understanding of the total picture, if not case by case. There is the ^{209}Bi anomaly, in the lead region. Yamazaki's work pointed out that this is a kind of general characteristic of high-spin states, and there we have calculated the δg_ℓ; many people have calculated this, and the picture on the whole is pretty good, but it is more complicated, being in heavier nuclei.

QUESTION 3: (Tony Thomas, TRIUMF)

In a sense it's a little early to start comparing these two theories with experiments since the MIT bag still has a lot of work to do in putting in coupling to pions. I think the small bag still has a long way to go to become a real theory. I would just like to point out that its implications for the P3-3 resonance are rather interesting and it leaves quite a different picture of pi-nucleon scattering in that energy region.

ANSWER:

I know this is all pretty preliminary. I would say we understand phenomenologically how to couple pions to the MIT bag; the MIT people don't like this but to me it seems rather forceful. At least for the second half of my talk I wanted to talk about things I foresaw for the next 10 years. If I knew how to do all of these things I would have put them into the first half of my talk.

Rosen: Well, I know that it was very difficult for Gerry to meet with us today. We appreciate the effort and let's thank him for making it.

☆U.S. Government Printing Office: 1980 — 677-115/109