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NUCLEAR HADRODYNAMICS

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ABSTRACT

The role of hadron dynamics in the nucleus is illustrated to show the importance of nuclear medium effects in hadron interactions. The low lying hadron spectrum is considered to provide the natural collective variables for nuclear systems. Recent studies of nucleon-nucleon and delta-nucleon interactions are reviewed, with emphasis on the type of experimental phenomena which signal the importance of the many-body dynamics.

In this talk I want to discuss what happens to hadrons in nuclei, not as revealed at high momentum transfer as in the EMC effect, but at relatively low momentum transfer in the interactions of hadrons. So, for the bulk of my talk, quarks and Quantum Chromodynamics will not be mentioned. This is not from a lack of appreciation of the importance of an underlying theory of strong interactions; it is rather from an important lesson that has been drummed into us in many body physics: Natural collective degrees of freedom are to be treasured, for often they provide the most economical description of a physical system. This stands out in all fields of many body physics, from the collective giant resonances and deformed shapes in nuclear physics to plasma oscillations, cooper pairs, rotons and paramagnons in condensed matter physics to a dynamical bag surface for hadrons in particle physics. The hadron spectrum suggests the appropriate collective variables in low-energy QCD are the nucleon, the delta (1232) and the low lying meson states, namely the "familiar" variables in use in nuclear physics. They are not a complete set, but they serve the vital role of characterizing phenomena and providing simple physical insight into concepts which must emerge from a more fundamental theory. It is the achievement of this insight that is the goal and the substance of nuclear hadrodynamics.

I will consider three related topics to show the power of a hadrodynamic description of the nucleus. Since I am an experimentalist, I will not dwell at all on the important progress in many-body theory. It is well known that nuclear theorists who want to do an easy problem for a change often calculate properties of liquid ^{4}He and ^{3}He. I will concentrate on the experimental signatures of hadron dynamics. The first topic is the nucleon-nucleon interaction in the nuclear medium. Next, I will discuss one of the most rapidly advancing areas of medium energy physics, the behavior of the $\Delta(1232)$ isobar in nuclear material. Finally, to reemphasize the unity of the subject and the relationship of the many-body dynamics to the rest of the field, considering the effects of isobars in nuclear states at low excitation energy will show that the excited states of the nucleon modify even ground state, properties.

The nucleon-nucleon interaction has proven to be one of the most difficult problems in modern physics. In the infancy of the subject, it led to the prediction of the existence of the pion.[1] Modern variations are concentrating on extracting the short range behavior from QCD.[2] This subject has emphasized the importance of non-locality[3] (as manifested, for example, directly in the nucleon mean free path), density dependent effects[4] (in accurate descriptions of nuclear ground states) and encouraged physicists to remember that the world is not spherically symmetric (a continuing stream of personal rediscoveries of the d-state admixture in the deuteron appear in the literature).

The advance of the last few years is that experiments have found convincing signals which provide direct evidence of the density dependence of the nuclear forces and show that much of the explanation is in hand. To do this one needs to look at nuclear excitations whose structure is known. Electron scattering provides the quantitative probe to extract, in a nearly model independent way, nuclear structure amplitudes as a function of momentum transfer, or equivalently, radius, for selected nuclear excitations. Figure 1 shows the radial form factors for the excitation of two strong states in ^{16}O, a 1^- and a 3^- state.[5]

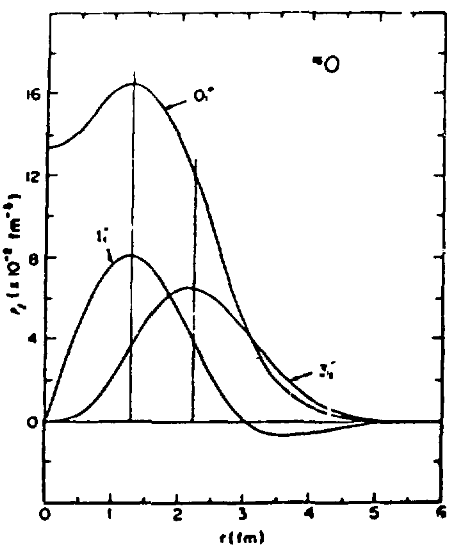

Fig. 1. Point nucleon density for the ground state and transition densities for the lowest 1^- and 3^- states in ^{16}O. (ref. 8)

With the nuclear structure under control we can look at inelastic proton scattering to these states (Figure 2). The curves represent calculations using a density independent nucleon-nucleon interaction. (The difference between the dashed and solid curves represent different choices of optical potentials). The large negative analyzing power at $q \approx 2.3$ fm^{-1} is extremely difficult to reproduce for the 1^- transition. Remember that the amplitude for this state peaks much more in the interior of the nucleus than that for the 3^- transition, suggesting density dependent effects may be more important. Figure 3 shows the calculated density

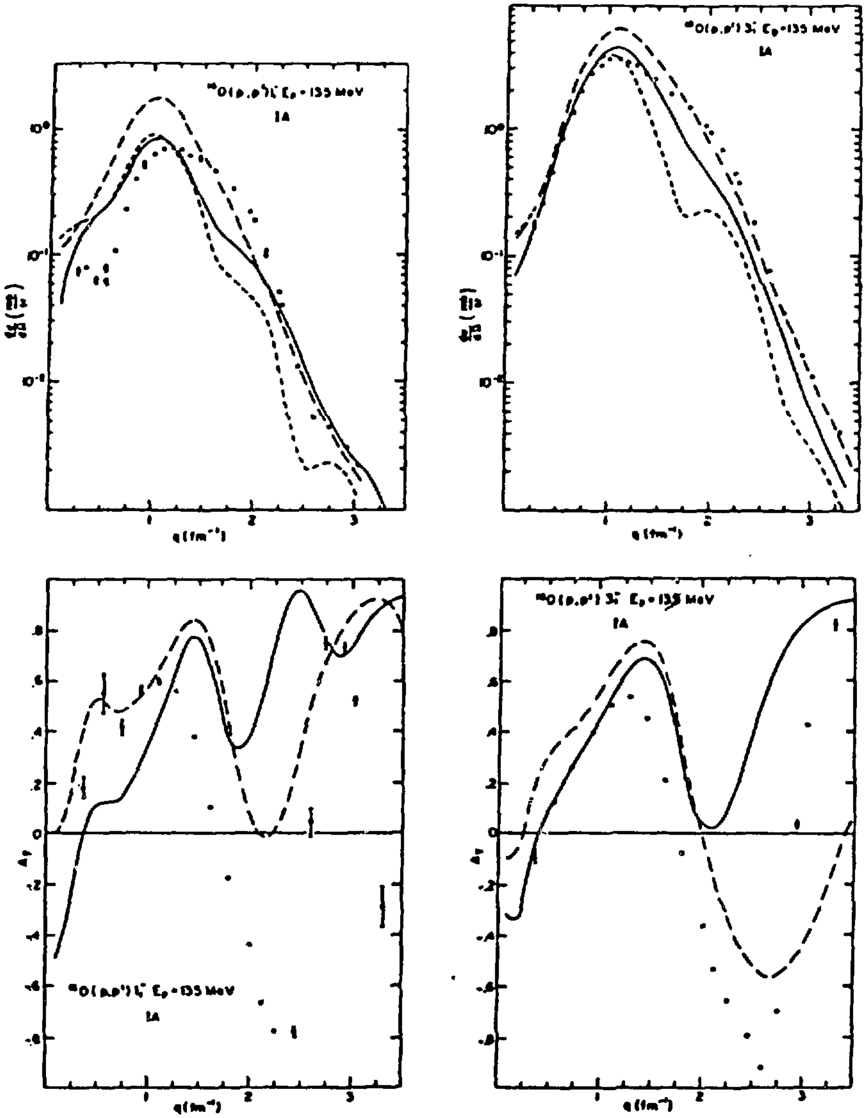

Fig. 2. Cross sections and analyzing powers for the excitation of the lowest 1^- and 3^- levels in ^{16}O by 135 MeV protons. The curves are impulse approximation calculations: phenomenological optical potential (long dashed), phenomenological optical potential without inelastic $\bar{L}\cdot\bar{S}$ contributions (short dashed), distorted waves consistent with effective interaction (solid). (ref. 8)

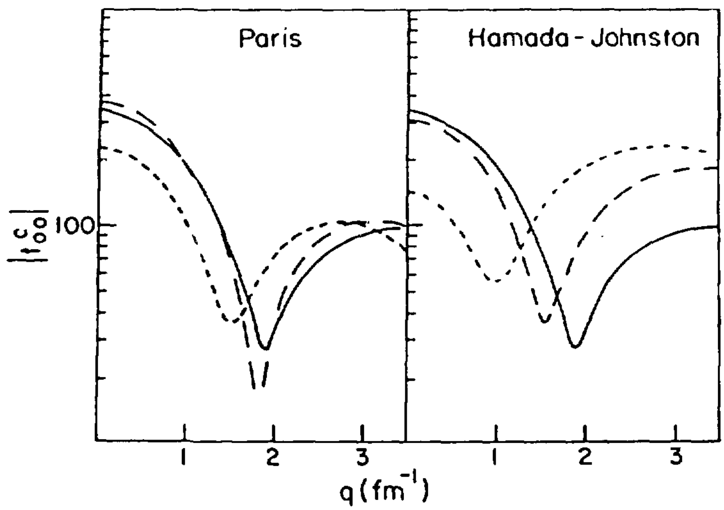

Fig. 3. Comparison of the density dependence of the Paris and Hamada-Johnston potentials and an effective interaction (solid) for the isoscalar spin-independent central interaction. Long (short) dashed curves are the low (high) density limits. (ref. 8)

dependence expected for the central nucleon-nucleon interaction in infinite nuclear matter.[6,7] On the other hand, the spin-orbit interaction is calculated not to be sensitive to the density. With the local density approximation, calculations including this density dependence reproduce the general features of the analyzing power very nicely. (Figure 4) The rather clear experimental signature has been identified thanks to the close interplay between the electron and hadron data. New work in this area is progressing rapidly. Enough cases have been studied so that a phenomenological density dependent interaction has been constructed and is being applied to the extraction of neutron density distributions with a Fourier-Bessel analysis similar to the electron scattering work.[8] This is shown in Figure 5 where the neutron and proton distributions for two 2^+ states in ^{18}O are illustrated. These radial distributions are important elements of the structure which have only been studied carefully in the past few years for proton distributions. The long history of taking the shell model for granted, because it gets the angular momentum right, is over.

Now, consider a distinguishable particle in the nuclear medium, the delta (1232 MeV). One view is that this tags a baryon in the nucleus; this is one of the primary motivations for the study of hypernuclei. From my point of view a more compelling reason for studying delta-nucleus dynamics is that the pion-nucleon and photon-nucleon interactions are dominated by the Δ

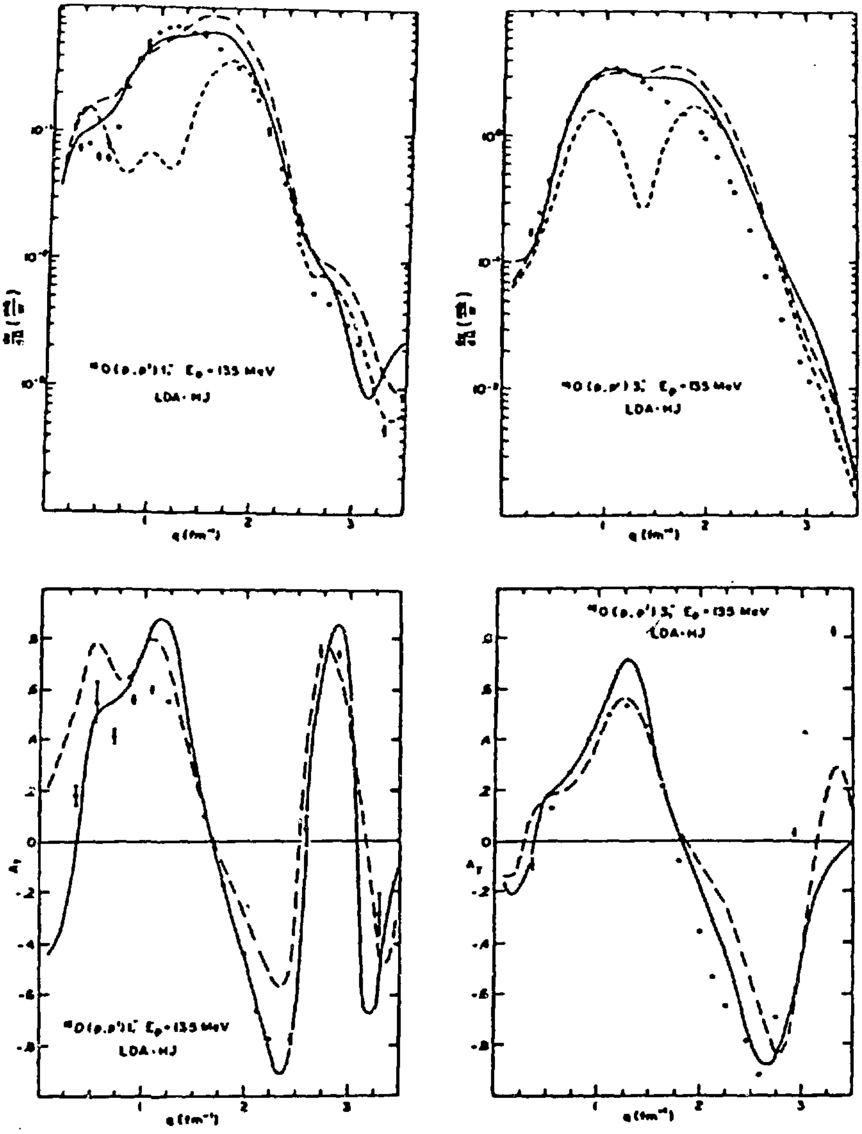

Fig. 4. Local density approximation calculations using the Hamada-Johnston effective interaction. The differences between the calculations are the same as in Figure 2. (ref. 8)

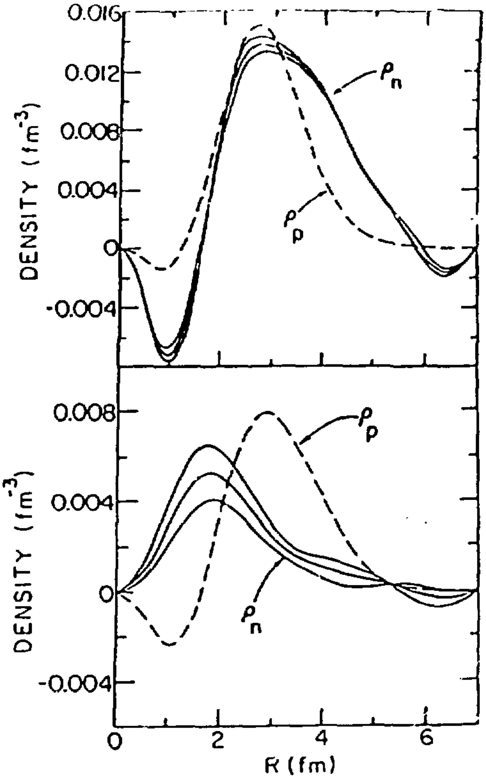

Fig. 5. The neutron and proton density distributions for transitions to the first and third 2^+ state in ^{18}O. (ref. 8)

resonance at "medium energies."[9] Figure 6 shows the energy dependence of the total photo-absorption cross section on Be, Pb and U. In contrast to the usual situation in nuclei where E1 amplitudes dominant, here it is magnetic contributions which dominate. This is a manifestation that the nucleon is absorbing most of the energy.

Pion-nucleus reactions provide the bulk of the information on delta dynamics. How should we describe a T_π = 200 MeV pion in the nucleus? There are real problems with identifying the "natural" degrees of freedom here. Some of the various scales characterizing the problem are listed in Table I. The strong π-nucleon interaction on resonance implies an interaction radius of ~2.5 fm,

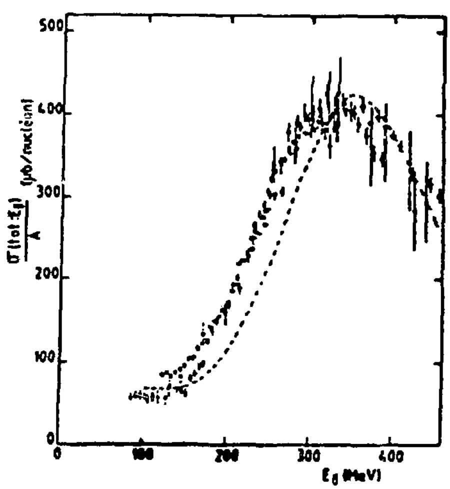

Fig. 6. Total photo absorption cross sections for Be, Pb and U measured at Bonn, Saclay and Mainz.

Table I Scales of π-nucleus interaction

		R(fm)
$\lambda\!\!\!^{-}$	$\hbar/p_\pi^{c.m.}$	0.9
σ_{π^+p}	$8\pi\lambda\!\!\!^{-2} \approx \pi R^2$	2.5
σ_{π^-p}	$8\pi\lambda\!\!\!^{-2}/9 \approx \pi R^2$	0.3
Δ Decay	$v\tau \approx p_\pi^{lab} \frac{2\hbar c}{M_\Delta \Gamma_\Delta}$	0.8
	$c\tau$	3.4
N-N Separation	$(\rho_0)^{-1/3}$	1.8
Radius	^{16}O	2.6
	^{208}Pb	6.6

to be compared with an internucleon spacing of ~1.8 fm, and a reduced pion wavelength of ~.9 fm. A Δ formed in a π-N interaction will typically have a kinetic energy of ~40 MeV, a velocity of ~.25 c and will travel only ~.8 fm before decaying back into a pion and a nucleon. The information about the delta must be carried by fast on shell pions (β ~.85) and off-shell mesons, yet the large range means the pions can interact with any one of several nucleons at one time.

This comparison suggests that the natural degrees of freedom are those of the delta propagating rapidly through the nucleus, so that a large fraction of nucleus is involved in the interaction. The limit of this approach is to diagonalize the interaction between a Δ and the A-1 nucleons, to consider a Δ-hole state. The virtue of this description is that most of the dynamics has been reduced to describing the propagation of the delta in the nuclear medium. This information is contained in the delta propagator:[10,11]

$$G^{-1} = E - H_\Delta - \omega - \delta\omega - W_{sp} \quad (1)$$

The power of the approach is the vast range of phenomena that can be considered in one framework: pion elastic scattering, inelastic scattering to discrete states and to the continuum, pion absorption, photon absorption, photo-pion reactions and many more. (See ref. 9)

The diagonalization of the delta-nucleus interaction reveals that in each partial wave a single Δ-particle, nucleon-hole state usually dominates the nuclear response. This collective state serves as a "doorway state" to reach all the various outgoing channels, in analogy to the collective giant dipole resonance in low energy photon reactions where a linear combination of 1-particle, 1-hole states serves as a collective doorway state. In the pion case it is a linear combination of 1-delta, 1-hole state..

Compared to the delta in free space, the additional terms in eq. 1 represent the obvious changes to the delta in the medium. The width for decay into $\pi + N$ will be reduced ($\delta\omega$) due to Pauli blocking of final nucleon states. True pion absorption through the delta will increase the delta width (W_{sp}) and pion induced rescattering gives an additional interaction (ω). Some of these can be calculated but the rest must be collected into a phenomenological Δ-nucleus interaction:

$$W_{sp} = W_o(E)\rho(R) + 2\ \bar{L}_\Delta \cdot \bar{\Sigma}_\Delta\ V_{LS}(R). \qquad (2)$$

The central and spin orbit terms are required to fit the data with a smooth energy dependence[12] (Tensor forces are also allowed and calculations[13] have suggested that they may be important as may more complicated density dependence than is contained in eq. 2). Figures 7 and 8 show the results for the distribution of reaction strength and for elastic scattering and give some evidence for the high quality of the description of the data that is possible.

In Table II, the values of the real and imaginary parts of the Δ-nuclear central and spin orbit potentials are compared to those for nucleon-nucleus and hyperon-nucleus interactions. The real part of the central potential is ~1/2 as strong as that for comparable velocity protons, while the imaginary potential is a factor of ~3 stronger. The difference in imaginary potentials is easy to understand; the nucleon absorptive potential only reflects nuclear excitations while the delta potential contains the strong true absorption. The real part of the delta and nucleon spin-orbit potentials are comparable while the lambda spin-orbit potential is essentially zero. Pirner has shown[16], in a simple additive quark model where the hadron-nucleus interaction is governed by quark exchange, that the p, Δ, Λ, and the Σ spin-orbit interactions should be in the ratio of 1 : 1 : 0 : 4/3. The observation that the Λ spin-orbit interaction is zero is one of the most appealing results of hypernuclear studies. (The usual duality exists here; this result can also be obtained in meson exchange models, but this was not at all obvious before the measurements.[17]) The Δ L•S force seems to fall into this picture and the Σ $\bar{L}\cdot\bar{S}$ force still needs to be reliably determined.

One remarkable feature in the isobar-hole model is that the spin-orbit interaction can be determined even though the individual states are broad compared to the splitting of the L•S interaction. The effect of the spin alignment on the pion-nucleus dynamics makes its presence felt. As an aside, these studies of pion absorption in nuclei have important consequences in proton

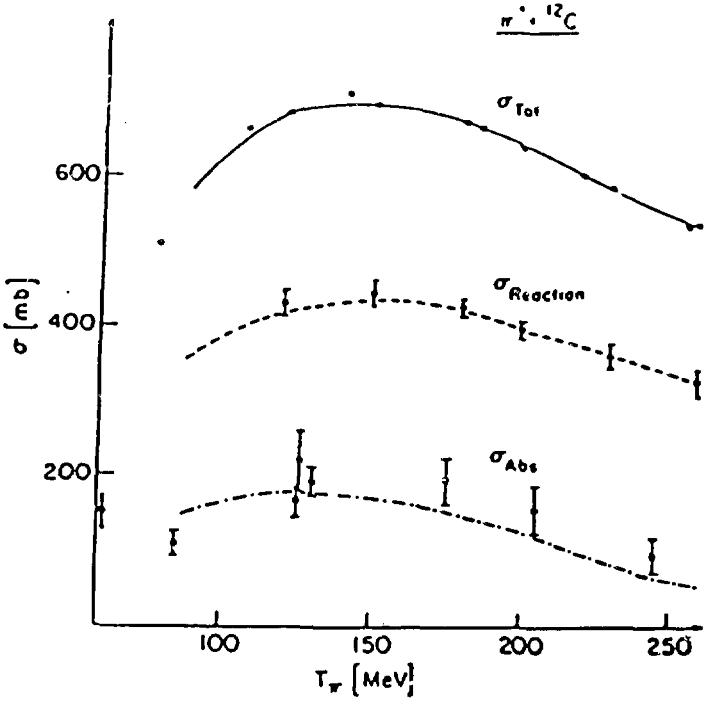

Fig. 7. $\pi^+ + {}^{12}C$, total cross sections, reaction cross sections and absorption cross sections. The curves are the results of fitting the spreading potential in the Δ-hole model.

Fig. 8. Elastic scattering of 163 MeV π^+ by ^{16}O. The solid curve is the full Δ-hole calculation including the $\vec{L}\cdot\vec{S}$ interaction while for the dashed curve the L·S interaction was not included. (ref. 12)

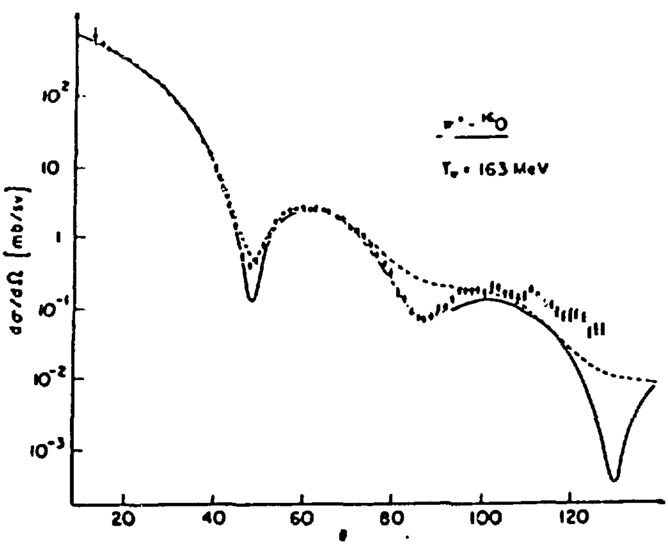

Table II Single Baryon Potentials*

	Phenomenology		Quark Model
	Central K_c ($MeV\ fm^3$)	Spin-Orbit K_{so} ($MeV\ fm^3$)	Relative Spin-Orbit
Nucleon (40 MeV)	370 + 100i	340 + 20i	1
Δ	160 + 290i	400 + 160i	1
Λ (hypernuclei)	260	0 ± 70	0
Σ			4/3

$$^{*}K_c = \int_0^\infty 4\pi\ U(r)r^2 dr/A$$

$$K_{so} = \int_0^\infty 4\pi\ U(r)r^2 dr/A^{1/3}$$

decay experiments that seek to look at back-to-back e-π^0 branches, since a simple estimate indicates that more than 50% of the pions emitted within an ^{16}O nucleus will be absorbed or scattered to a significant angle with respect to their original direction.[18]

Once one has a delta single-particle potential it is still non-trivial to separate the many body effects from the bare interaction, or changes in the Δ self energy from vertex corrections to the interaction.[19] The next step is to go deeper in search of the Δ-nucleon interaction. Here we are making connections to the nucleon-nucleon interaction, to questions of pion-production and absorption and to di-baryon resonances. One nice way to study this is to look at pion absorption on T=0, S=1 pairs of nucleons ($d(\pi^+,p)p$ or $^3He(\pi^+,pp)p$) and absorption on T=1, S=0 pairs ($^3He(\pi^-,pn)n$. The Pauli principle allows the first reaction to go through a Δ-N S wave state, but in the second interaction the delta and nucleon must be in a relative p wave or higher (f, h, ... $(-1)^\ell = -1$). We can also look for interference between delta and non-delta parts of the interaction, particularly in the weaker p-wave channels. Figure 9 shows angular distributions for studies at 65 and 165 MeV from TRIUMF[20] and LAMPF.[21] In the strong $(\pi^+,2p)$ absorption channel, the angular distributions are symmetric, about 90°, and well fit by Δ-nucleon models. In the weaker π^- absorption, the definite asymmetry seen at 65 MeV, on the order of 1 full Δ width away from the peak of the resonance, shows that concentrating only on the delta dynamics is insufficient. At 165 MeV the π^- angular distribution is

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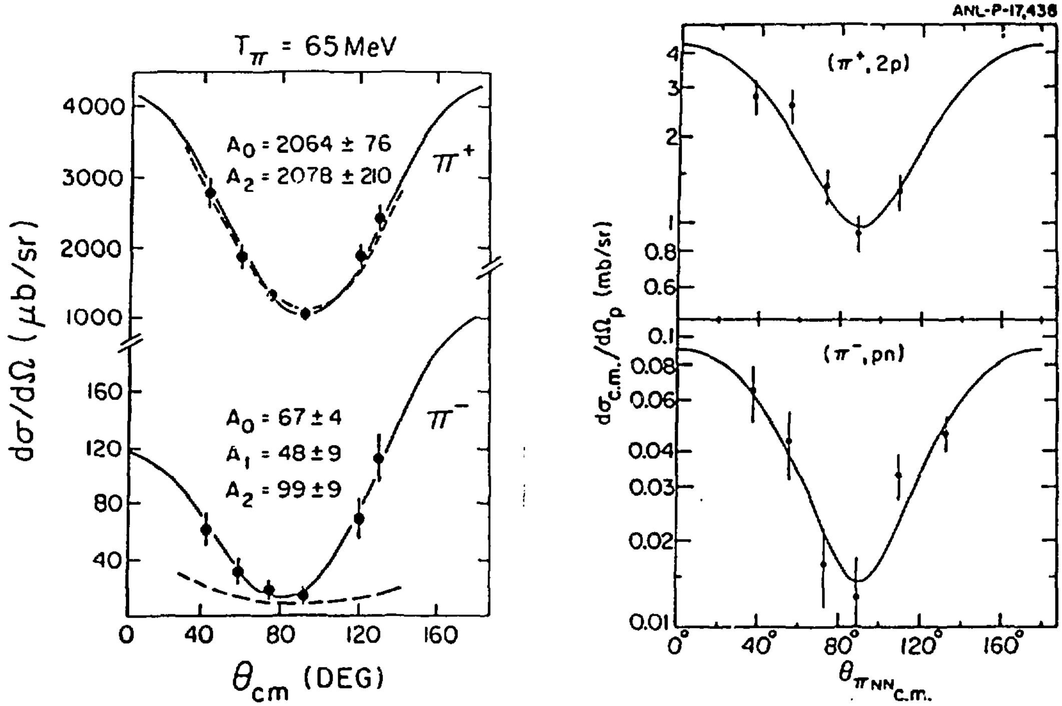

Fig. 9. Differential cross sections for the two-body portion of the reactions $^3He(\pi^+, 2p)p$ and $^3He(\pi^-, pn)n$ at T_π = 65 MeV (left) and 165 MeV (right). The solid curves are Legendre polynomial fits to the data.

symmetric, but the cross section is not fit by calculations which include only Δ-nucleon intermediate states. Here we are seeing the isobar-nucleus model breaking down, but we are doing it by concentrating on reaction channels where it is expected to be weak, i.e. forcing the delta and nucleon to be in a relative p-wave.

Once we specifically consider the delta-nucleon interaction, we have new mechanisms to excite a nucleus. These are shown diagramatically in [redacted]. With a model of the delta-nucleon interaction we can, in principle, solve the many body problem and separate the different contributions.[19] For elastic scattering both self energy and vertex corrections have the same effect. They appear as an energy shift in the propagator. A clearer signal of the importance of these effects can be revealed in inelastic scattering, especially for particular isospin dependences of the Δ-N interaction.

One of the high expectations for pion-nucleus physics was that one could use the simple isospin dependence of the π-N interaction to study nuclear structure. The $P_{3,3}$ amplitude can be written as:

$$t = \frac{e^{i\delta}}{k} \sin\delta \left[\frac{2 + t \cdot \tau}{3}\right] \left[2\cos\theta + \bar{\sigma}\cdot\hat{n} \sin\theta\right] . \qquad (3)$$

Medium corrections which simply change the phase shift preserve the isospin and spin selectivity. However a T=1, S=2 Δ-N interaction which can excite nuclear states will change this. The impulse approximation says that isoscalar states will be excited a factor of four stronger than isovector states of the same internal structure. Hirata, Lenz and Thies estimate[19] that for low spin states the spreading potential, which is strong due to true absorption in the T=1, S=2 channel changes the impulse approximation result by a relative factor:

$$\tilde{\rho} = (-1)^{T_f+1} \frac{\alpha |W_{sp}|}{\Gamma/2 + \alpha |W_{sp}|} \tag{4}$$

where $\alpha \sim .3$. This implies a correction of $\sim .2\ (-1)^{T_f+1}$, and changes the 4 to 1 ratio between isocalar and isovector states to

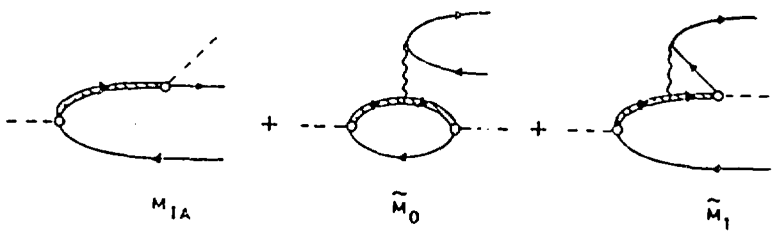

Fig. 10. Graphical representation of pion inelastic scattering including impulse approximation (M_{IA}) and contributions from Δ-N two body interaction ($\tilde{M}_0$ and $\tilde{M}_1$). (ref. 19)

~2 to 1. Similarly in quasifree scattering, the relative corrections to the 3 to 1, π^+p to π^+n, amplitudes are:

$$\tilde{\rho} = \begin{cases} -.08 & \pi^+p \to \pi^+p \\ 0.23 & \pi^+p \to \pi^o n \\ -.70 & \pi^+n \to \pi^+n \end{cases}$$

The results[22] of the SIN group for $^{16}O(\pi, \pi p)$ in the quasifree region are shown in Figure 11 along with an isobar-hole prediction, The ratio $\sigma(\pi^+)/\sigma(\pi^-)$ varies considerably from the free ratio of 9 and is generally accounted for by the calculation. I find this a dramatic confirmation of the effects of the Δ-N interaction.

The results for inelastic scattering for the T=0 and T=1 1^+ states in ^{12}C are shown in Figure 12. The qualitative reduction of the ratio $\sigma_{T=0}/\sigma_{T=1}$ is in line with the Δ-hole calculation. Here though I want to sound a personal word of warning. The structure of isoscalar spin-flip excitations is very poorly understood. This is the least studied mode of the nuclear response due to the fact that very few probes are selective for such excitations. The ratio of the summed isoscalar strength to summed isovector strength for high spin states[24] has been shown to be ~1/2-1/3. For these transitions with surface dominated form factors, the medium effects are calculated to be much less important and there seems to be a substantial reduction of isoscalar spin-flip strength relative to the isovector spin-flip strength due to nuclear structure. (This may reveal a large short-ranged spin-spin component to the nucleon-nucleon effective interaction.) While I find the nuclear structure aspects of this fascinating, it means we cannot draw any firm conclusions from the ratio of cross sections for the 1^+ states other than the general one that the Δ-N interaction does seem to help fit the experimental ratio.

In pion or photon induced reactions, it may be obvious that deltas are important degrees of freedom. What was not obvious, until of course it was published, was that delta-hole states can affect low-lying nuclear excitations.[25] At incident energies of ~200 MeV (p,n) charge exchange reactions have proven to be remarkably selective probes of isovector spin flip excitations. As in many other places in physics, it was the identification of a selective probe of one particular channel of the nuclear response which opened a new window on the dynamics. The fraction of the strength observed in 1^+ states relative to a sum rule limit is shown in Figure 13.[26] Typically only 50% of the Gamow-Teller ($|\langle 1^+||\sigma\tau||0\rangle|^2$) strength can be found. One explanation is that it is the delta-hole states which explain the missing strength. Consider 1^+ states such as those in ^{12}C. We have two classes of 1^+ excitations representing nucleon particle-hole states at energies of ~10 MeV above the ground state and delta-hole states which lie at ~300 MeV.

$$\begin{array}{lll} E \sim 0\text{-}2\ \hbar\omega & |NN^{-1}\ \alpha\rangle & T=0,1 \\ E \sim M_\Delta - M_N & |\Delta N^{-1}\ \beta\rangle & T=1,2 \end{array}$$

The matrix element of the spin operator connecting the nucleon to the delta is large; the delta is essentially a pure spin flip excitation in the quark model. In perturbation theory the wave function from a mixing of these two classes of states will be:

$$\psi \sim \sum_\alpha A_\alpha \left[|NN^{-1}\alpha\rangle + \sum_\beta \frac{\langle \Delta N^{-1}\beta|V|NN^{-1}\alpha\rangle}{M_\Delta - M_N} |\Delta N^{-1}\beta\rangle \right]$$

The delta is not restricted by the exclusion principle so many delta-hole states can contribute to the sum. Even though the energy denominator is large, matrix elements of spin operators may be reduced by ~20% in T=1 channels. I must emphasize that this is not the only, nor perhaps the largest correction to $\langle||\sigma\tau||\rangle$. There are higher order nuclear structure effects and meson exchange currents which are important. But the delta effect is certainly there and one can relate the effects of the deltas in nuclear structure to the ΔN-NN interaction discussed above. The most direct experimental evidence of this is work[27] on (^{3}He,t)

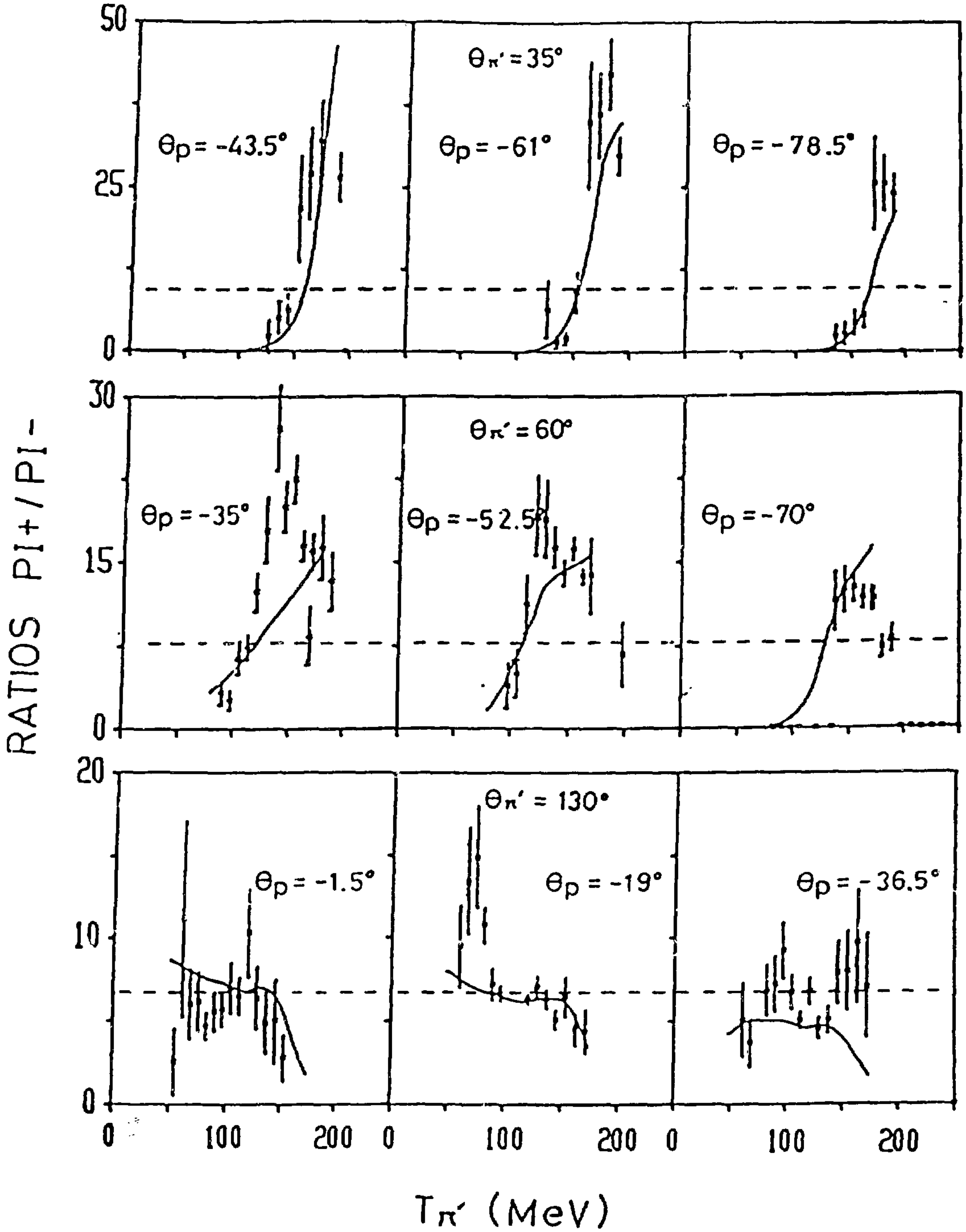

Fig. 11. Ratios of the five-fold differential cross sections for $(\pi^+, \pi^+p)/(\pi^-, \pi^-p)$ for $p_{1/2}$ removal from ^{16}O for pion scattering at 35°, 60° and 130°. The solid lines are the results of the delta-hole calculations including Δ-N interactions. (ref. 22) The dashed lines of the ratio of cross sections on a free proton.

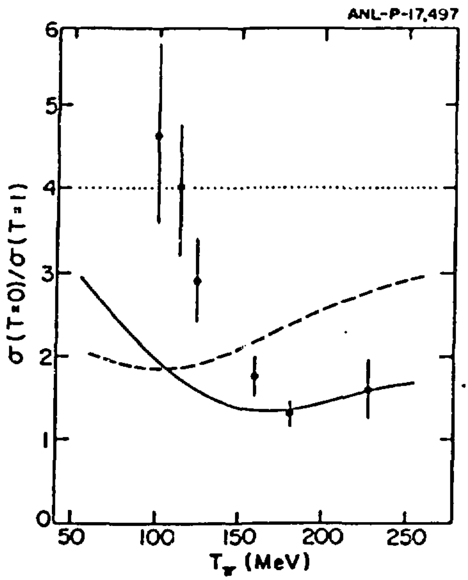

Fig. 12. Ratio of cross sections from pion inelastic scattering to the 12.71 MeV T=0, 1^+ and 15.11 MeV T=1 1^+ states in ^{12}C. The curves are the results of delta-hole calculations.

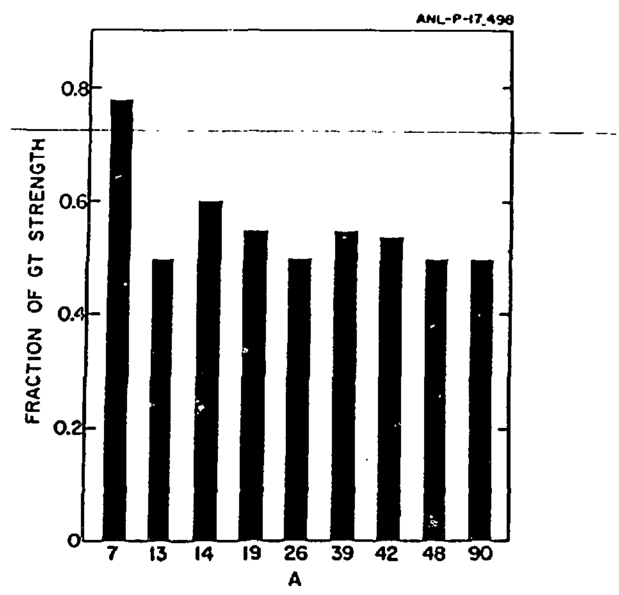

Fig. 13. Fraction of the Gamow-Teller sum rule strength identified in (p,n) reactions.

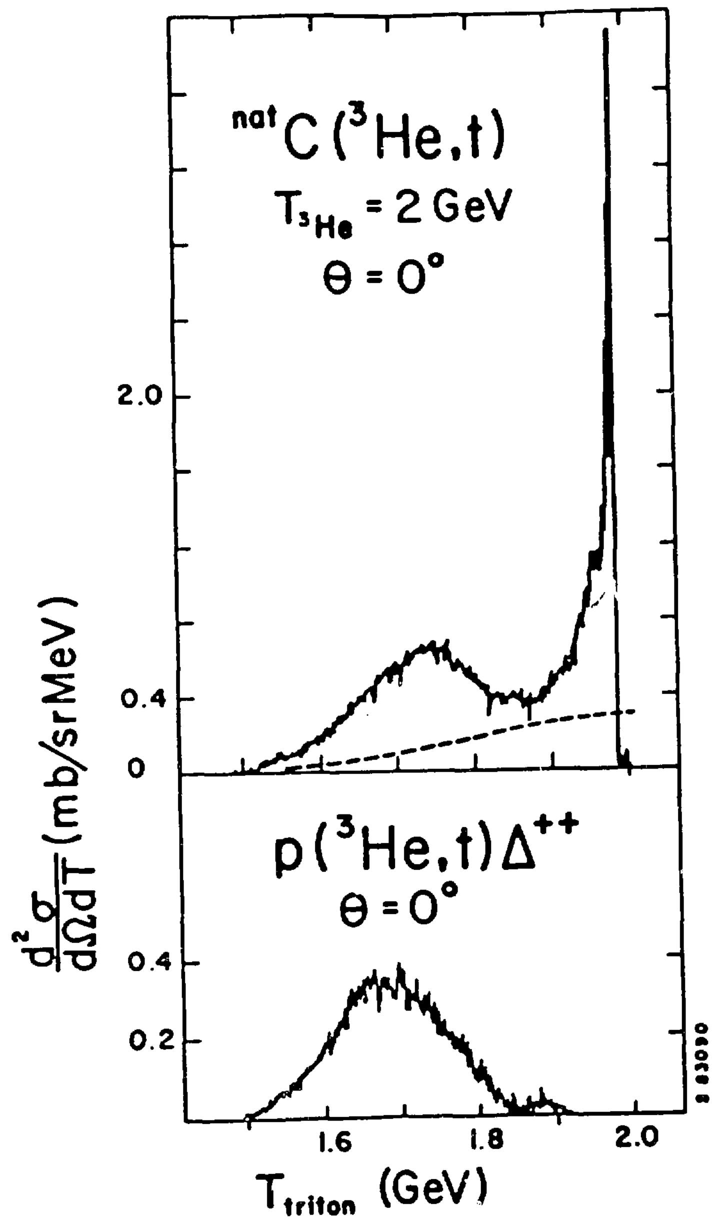

Fig. 14. Triton spectra at zero degrees from ^{3}He-bombardment of carbon and hydrogen. (ref. 27)

reactions with 2000 MeV ^{3}He beams where the triton is detected at 0°. This reaction also selectively excites isovector spin-flip states and the experimental spectrum shown in Figure 14 very clearly reveals the low-lying excitation or Gamow-Teller resonance and the continuum delta-hole strength at 300 MeV excitation.

Another place to look for specific delta effects is in pion double charge exchange reactions. A preexisting Δ in nuclear matter provides a mechanism for a 1-step double charge exchange process. In a kinematic regime where successive single charge exchange reactions are inhibited, the signal for the prexisting delta will be enhanced. It has already been observed that there appear to be two distinct mechanisms at work in pion double charge exchange to discrete states.[28] We need more experimental and theoretical work to identify the mechanism.

In summary, I have shown several examples in which a knowledge of the dynamics of hadrons in nuclear material is important. The pervasiveness of this point of view is perhaps indicated by the observation that I have shown data from many laboratories obtained with a variety of probes of the nucleus. For most of these applications, we are far from the regime where we understand how to apply QCD to nuclear phenomena. We have built our understanding upon what appear to be the natural collective variables of nuclear systems in our strong coupling situation. This has given us tremendous power in understanding nuclei and a far surer rule to be "proved" by the underlying quark dynamics.

I would like to thank J. Kelly and C. Gaarde for making their unpublished results available.

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