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The Theory of Hadronic Systems Annual Progress Report DOE Grant No. DE-FG03-92ER40740

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Chapter 1

Introduction

This report summarizes the work on theoretical research in the area of the hadronic interaction carried out at New Mexico State University in 1993-1994 under grant DE-FG03-92ER40740 from the Department of Energy.

The research activities are in several areas united by the central theme of the study of the hadronic interaction. An underlying theme of the work is an attempt to understand the strong interaction in the full sense of the word; not only its fundamental source but the way in which it manifests itself in the systems it binds. These may be nuclei or smaller systems, such as composite mesonic states or the nucleons themselves.

Following is a summary of the principal recent and current activities in this area.

Chapter 2

Research Summary

2.1 Isospin Breaking in the Pion-Nucleon System

The study of a classification of isospin breaking in the pion-nucleon system was recently completed and published[4]. It takes the form of a tensorial ranking in isospin with certain ranks (and specific operators) being associated with given physical origins. For example, ρ–ω mixing has a definite isospin-breaking character in the pion-nucleon interaction.

We are now analyzing the experimental evidence for isospin breaking in the πN system. Most evidence for such breaking is negative except for pion-deuteron scattering. The total cross section measurements[5] on deuterium, using both π^+ and π^- beams, show a clear difference in the two cross sections, usually interpreted as due the mass differences in the four charge states of the Δ resonance which are, in turn, thought to arise from the mass differences of the up and down quarks and the Coulomb interaction. Charge asymmetry measurements of the differential cross section from deuterium also exist[7, 8] and we continue to analyze these measurements.

The direct analysis of low-energy π-nucleon data for isospin breaking is a current project of high priority. Recent measurements of pion-nucleon scattering have provided data of exceptionally high quality below and around 50 MeV, in particular

$\pi^{\pm}$ Scattering

J. S. Frank et al., *Phys. Rev.* **D28**, 1569(1983)
J. T. Brack et al., *Phys. Rev.* **C41**, 2202(1990); C38, 2427(1988);
C34, 1771(1986)

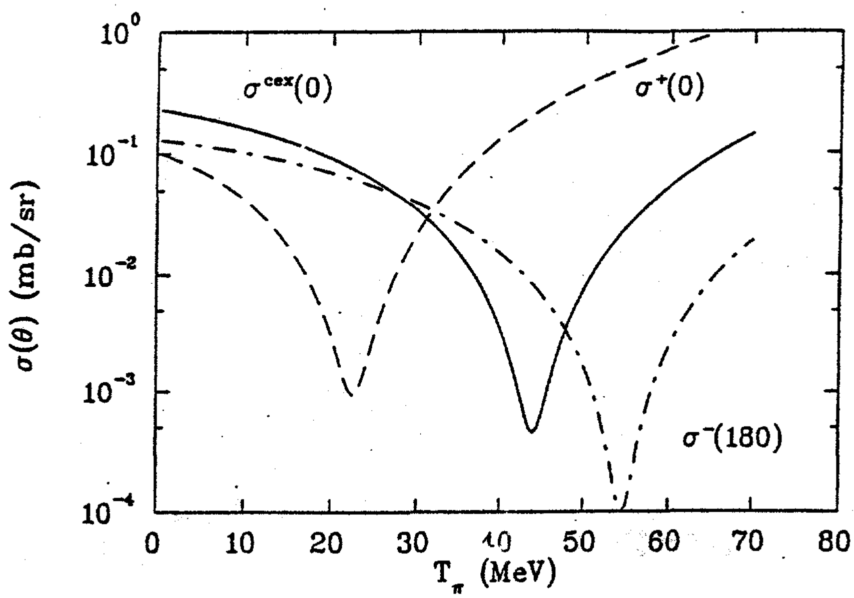

Figure 2.1: The three minima in the π^+p, π^-p, and charge exchange reactions.

U. Wieder et al., *Phys. Rev. Lett.* **58**, 648(1987)
C. Joram, πN Newsletter No. 3 (1991)

Pion charge exchange

D. H. Fitzgerald et al., *Phys. Rev.* **C34**, 619(1986)
M. E. Sadler et al., πN Newsletter, No. 5, 1992
M. Salomon et al., *Nucl. Phys.*, **A414**, 493(1984)
J. Duclos et al., *Phys. Lett.* **B43**, 245(1973)

One might ask why this energy is useful for the study of isospin breaking. Two reasons that we might cite are:

- The test of isospin by the "triangle rule",

$$\sqrt{2} f_{cex} = f_{\pi^+} - f_{\pi^-}$$

is facilitated by the existence of "zeros" (cancellation of the real parts of the amplitude) in any of the individual amplitudes so that the other two cross sections become equal. There is a "zero" in each of the amplitudes in this energy range. See Figure 2.1. At these low energies the imaginary part of the amplitude is very small.

- The amplitudes have a smooth (and slow) energy dependence so that fits of models are unambiguous.

We are fitting potential models of the amplitudes to the charged pion data and using them to predict the charge-exchange data by the "triangle rule" relation, Eq. 2.1. The data have a claimed precision of the order of 2% which implies an error on the predicted charge-exchange amplitude of the order of ±0.002 fm.

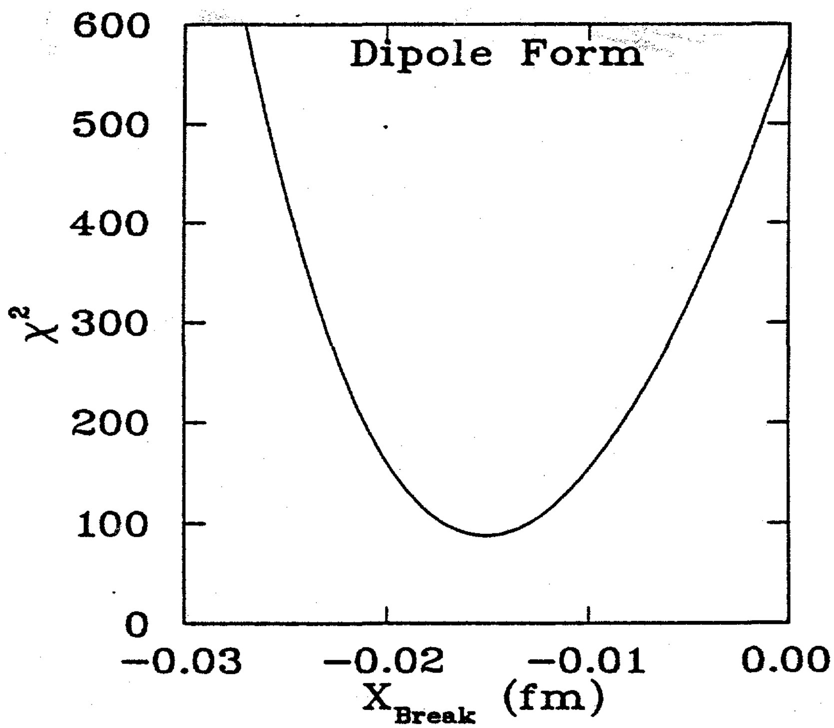

Figure 2.2: The χ^2 for the fit to the charge exchange data is shown as a function of the assumed breaking in the s-wave of the charge exchange amplitude. We are currently studying the effect of the inclusion of a p-wave term

The minimum in the charge exchange cross section at zero degrees is of crucial importance since its position can be determined much more precisely experimentally than the absolute magnitude of the cross section.

Figure 2.2 shows the χ^2 which results from the addition of an assumed s-wave breaking component to the charge exchange amplitudes. Of course one cannot tell from the present work where the breaking occurs in Eq. 2.1; it could as well be in the charge exchange or the π^+/π^- scattering (or a combination of the two). The meson contributions to the isospin breaking amplitude are $\pi\eta$ mixing in charge exchange and $\rho\omega$ mixing in scattering (see [6] for a review of $\rho\omega$ mixing in the NN system). If the entire breaking is assumed to have the form of $\rho\omega$ mixing (the a_3 amplitude in our classification) the approximate size and sign are correct to explain the small breaking seen in low energy π-deuteron scattering. In order to separate the two effects in a more reliable way, an additional experiment needs to be done, perhaps $^3\mathrm{He}(\pi^-,\pi^0)^3\mathrm{H}$ compared with $^3\mathrm{H}(\pi^+,\pi^0)^3\mathrm{He}$ at zero degrees in the region of the charge-exchange minimum at low energies.

This work is being done in collaboration with Li Ai, Mohini Rawool-Sullivan and W. B. Kaufmann.

2.2 The np Charge-Exchange Reaction

Neutron-proton charge exchange near zero momentum transfer shows a sharp peak in the differential cross section as a function of angle. This is precisely where the long-range exchange of a charged pion should dominate, but one pion exchange gives zero cross section at $q = 0$. Investigation of the one-pion-exchange amplitude shows that removing the s-wave component leads to a cross section of about the right size. We noticed that the removal of the delta function in the one-pion-exchange potential can lead to a removal of the unwanted s-wave contribution if done in the context of pion exchange between the quarks which make up the nucleon. We have recently found that the same procedure predicts the spin-transfer observables very well.

If we put the center of mass of two nucleons at the origin then the centers of the two nucleons will be at $\frac{\mathbf{r}}{2}$ and $-\frac{\mathbf{r}}{2}$. The coordinates of the six quarks are then:

$$\mathbf{r}_1 = -\frac{\mathbf{r}}{2} + \mathbf{u}_1; \quad \mathbf{r}_2 = -\frac{\mathbf{r}}{2} + \mathbf{u}_2; \quad \mathbf{r}_3 = -\frac{\mathbf{r}}{2} + \mathbf{u}_3$$

$$\mathbf{r}_4 = \frac{\mathbf{r}}{2} + \mathbf{u}_4; \quad \mathbf{r}_5 = \frac{\mathbf{r}}{2} + \mathbf{u}_5; \quad \mathbf{r}_6 = \frac{\mathbf{r}}{2} + \mathbf{u}_6$$

where the vectors $\mathbf{u}_i$ are coordinates of the quarks relative to the center of mass of the nucleons. See Figure 2.3

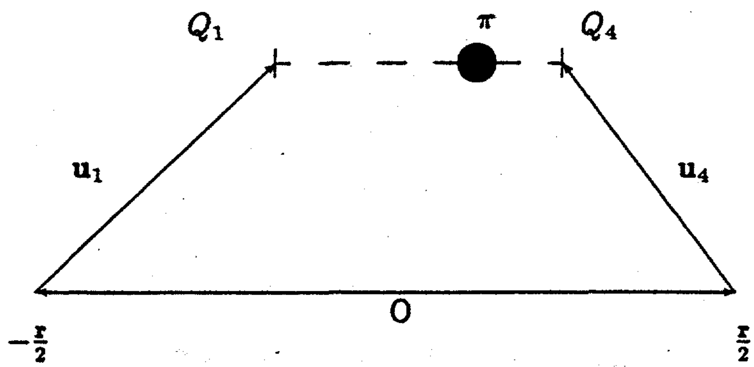

Figure 2.3: Cartoon of a pion being exchanged between quarks in two different nucleons.

Since the s-wave component of the one-pion-exchange amplitude is given by:

$$\frac{1}{4\pi}\int d\Omega \frac{\sigma_1\cdot\mathbf{q}\sigma_2\cdot\mathbf{q}}{q^2+\mu^2}=\frac{1}{3}\frac{q^2\sigma_1\cdot\sigma_2}{q^2+\mu^2}$$

it has a large-q limit of unity leading to a δ-function in the potential

$$V_0(r)\propto\mu^2\frac{e^{-\mu|\mathbf{r}_1-\mathbf{r}_2|}}{|\mathbf{r}_1-\mathbf{r}_2|}+\delta(\mathbf{r}_1-\mathbf{r}_2)$$

But for separations of the quarks which are less than the size of the pion we need to cut off the potential, perhaps with a form like;

$$V(r)=V_0(r)(1-e^{-(r/R)^2}).$$

Thus the modified amplitude becomes:

$$\frac{\sigma_1\cdot\mathbf{q}\sigma_2\cdot\mathbf{q}}{q^2+\mu^2}\rightarrow\frac{\sigma_1\cdot\mathbf{q}\sigma_2\cdot\mathbf{q}}{q^2+\mu^2}-\frac{1}{3}\sigma_1\cdot\sigma_2=\frac{1}{3}\frac{q^2S_{12}}{q^2+\mu^2}-\frac{1}{3}\frac{\sigma_1\cdot\sigma_2\mu^2}{q^2+\mu^2}$$

where $S_{12}\equiv 3\sigma_1\cdot\hat{\mathbf{q}}\sigma_2\cdot\hat{\mathbf{q}}-\sigma_1\cdot\sigma_2$. We see that it is only the spin-spin part of the amplitude (and potential) which is modified.

For charged pion exchange only, the cross section is given by

$$\sigma(q) = \frac{4}{3}N^2 g^2(q)\left[1 + 3f^2(q) - 2f(q)\right]$$

with

$$f(q) \equiv \frac{q^2}{q^2+\mu^2}; \quad g(q) \equiv \left(\frac{\Lambda^2}{q^2+\Lambda^2}\right)^2 \quad \text{[assuming a monopole form factor].}$$

The momentum transfer in these relations is given by $q^2 = 2k^2(1+\cos\theta)$, and the normalization of the cross section by:

$$N = \left(\frac{M_n}{m_\pi}\right)^2 \frac{1}{\sqrt{s}} \frac{f_\pi^2}{4\pi} \left(\frac{\Lambda^2-\mu^2}{\Lambda^2}\right)^2.$$

Here s is the square of the center-of-mass energy of the two nucleons. The factor of $\frac{1}{\sqrt{s}}$ provides a scaling factor which is observed to be consistent with the data over a range of beam energies from 200 MeV to 60 GeV.

The spin transfer observables are given by:

$$K_{SS}(q) = \frac{-\frac{1}{3} + 3f^2(q) - 2f(q)}{1 + 3f^2(q) - 2f(q)}$$

$$K_{LL}(q) = \frac{-\frac{1}{3} - 3f^2(q) + 2f(q)}{1 + 3f^2(q) - 2f(q)}$$

$$K_{NN}(q) = K_{LL}(q).$$

If the δ-function were **not removed** the values of the spin observables would be:

$$K_{NN} \equiv -1; \quad K_{SS} \equiv +1; \quad K_{LL} \equiv -1.$$

For the inclusion of both the charged and neutral one pion exchange the expressions for the amplitudes are only slightly more complicated. Comparison of these predictions with K_{NN} and K_{LL} is shown in Figure 2.2. The dashed curve shows the prediction from charged pion exchange alone while the two solid curves include the exchange of the neutral pion as well. Note that the data is largely independent of the beam energy as predicted.

The spin-spin component of the potential has the form

$$V_{ss}(r) = \frac{f^2}{4\pi}\left[\frac{e^{-\mu r} - e^{-\Lambda r}}{r} - \frac{\Lambda^2-\mu^2}{2\Lambda}e^{-\Lambda r}\right].$$

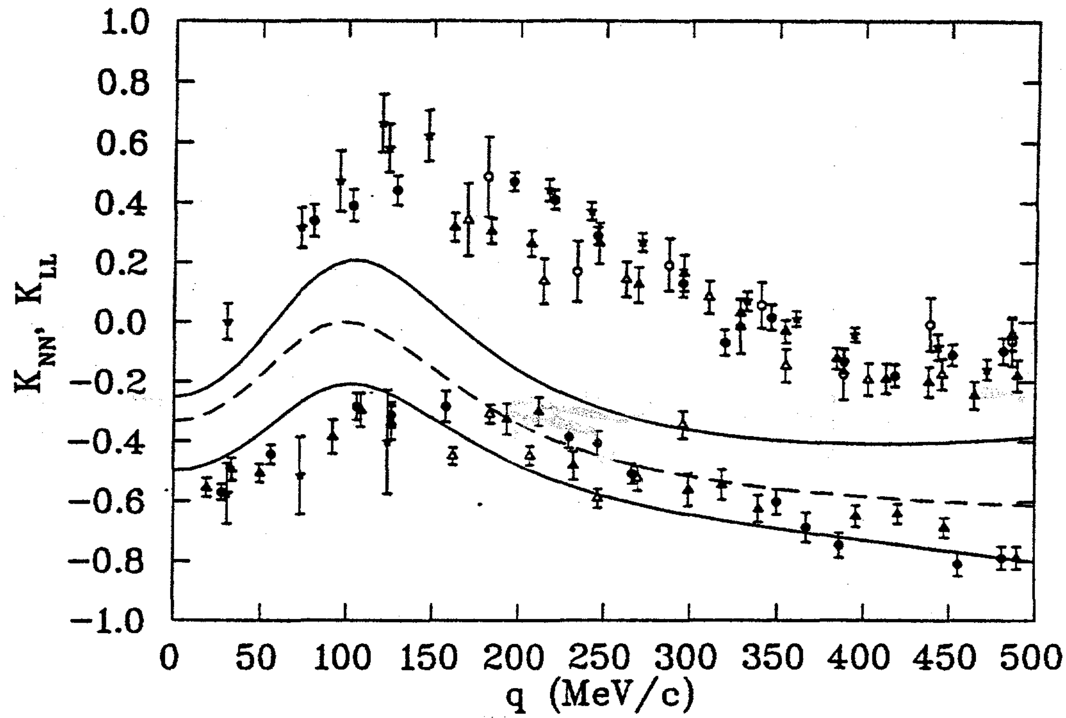

Figure 2.4: K_{NN} (bottom) and K_{LL} (top) as a function of momentum transfer. The data[9] include energies from 485 MeV to 788 MeV.

The potential with the δ-function (the original one-pion-exchange distributed over the quark density in the nucleon, or simply multiplied by a form factor for whatever reason) is given by

$$V_{ss}^{\delta}(r) = \frac{f^2}{4\pi}\left[\frac{e^{-\mu r} - e^{-\Lambda r}}{r} - \frac{\Lambda(\Lambda^2 - \mu^2)}{2\mu^2}e^{-\Lambda r}\right]$$

Thus the large difference seen in the cross section and spin-transfer observables is not at all obvious in the form of the potential. The difference is a little clearer when one observes that the coefficient of last term has the proper normalization for a δ-function in the limit of large Λ in the second case and not in the first.

This work is being done in collaboration with B. Loiseau.

2.3 Energy Dependence of Pion DCX

A resonant-like structure in low-energy pion double charge exchange has been known for some time. It manifests itself in a peak around 35-50 MeV pion kinetic energy.

In studies that we performed on elastic scattering some years ago we pointed out[11] that the cancellation of the s- and p-wave pion-nucleon amplitudes in this energy region leads to a transparency of the nuclear medium. If one calculates the effect from a fine volume of this material it was shown that poles in the S-matrix appear and there are a number of resonances in each pion-nucleus partial wave. These resonances are in the pion-nucleus system and become broader with higher energy. Normally only one or two might be expected to be visible. A partial wave separation would need to be performed in order to see their effect in elastic scattering.

Reactions, on the other hand, tend to show up this effect more clearly since a single (or few) partial waves tend to be more important. Our calculations[11] for a general monopole transition show a clear peak in this region. That is not to say that one can always accurately predict positions of the peak and absolute cross sections for reasons to be discussed below.

In spite of a general understanding of this effect in terms of (more or less) standard physics, a suggestion was recently made[10] that this data provided a signal for the existence of a dibaryon. The authors simply allowed themselves to make up the parameters which would fit the data, ignoring the fact that there had to be a peak in this energy region.

For this reason we were forced to do the calculations to show to what degree we do (and do not) understand the data. There are several problems once one is constrained to do a realistic calculation.

First, the reaction mechanism itself. From the work that we did on the double scattering operator[1] and the one pion exchange interaction in the neutron-proton charge-exchange reaction (see above) it can be seen that the δ-function needs to be removed from the DCX operator. This effect has never been investigated by any group (including our own) to my knowledge. Since this is a significant project its study will have to wait. A rapid calculation with plane waves (very crude for what we want to look at) shows that a considerable renormalization could result.

Second, the nuclear wave function. Since the relative distance between the two nucleons plays a strong role (that is, in fact, a large part of the interest in the reaction) small changes in the wave function can produce significantly different weightings of the pion-nucleus partial waves and hence change the weighting of the resonances. One might expect that, for certain cases, two or more of the resonances could be seen.

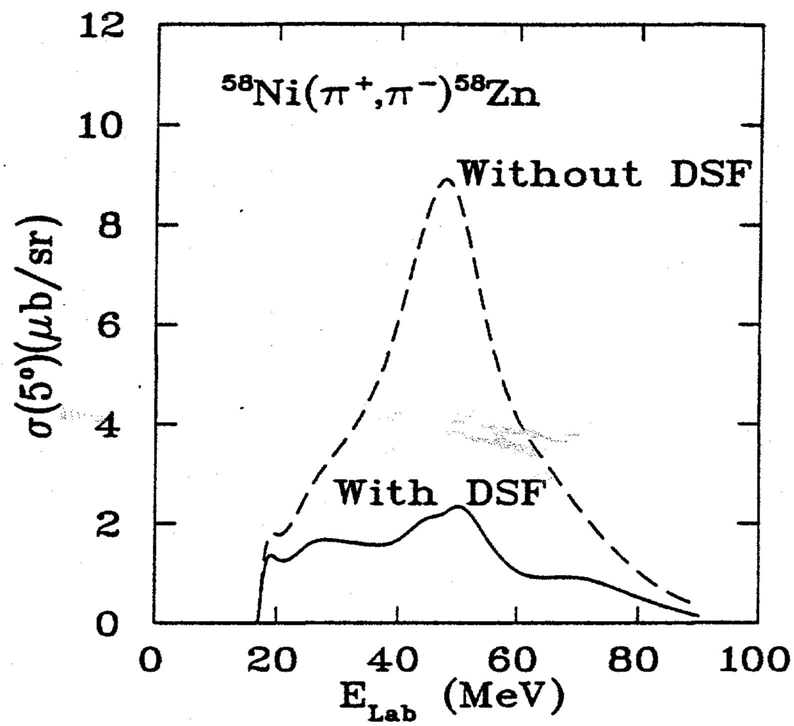

Figure 2.5: Pion double charge exchange on ^{58}Ni. The two curves show the calculation without and with double spin flip included.

Third, the propagation of the intermediate π^0. This uncertainty has two aspects; the optical model to describe the motion of the pion and the question of which excited states play a role. If one uses closure to sum over the intermediate states (as we do) then the double spin flip cancels, to a large extent, the non-spin-flip amplitude with the effect of decreasing the sharpness of the peak. The intermediate states corresponding to the double spin flip are the Gamow-Teller states which are claimed have a quenched strength. If this is true then the cancellation will be reduced and the observed resonance seen in DCX will be stronger.

Fourth, the optical model itself. This is the description of the incoming and outgoing waves. In general we have what we think is a reasonable model of this part of the reaction but improvements can certainly be made. The principal variable in this part of the model

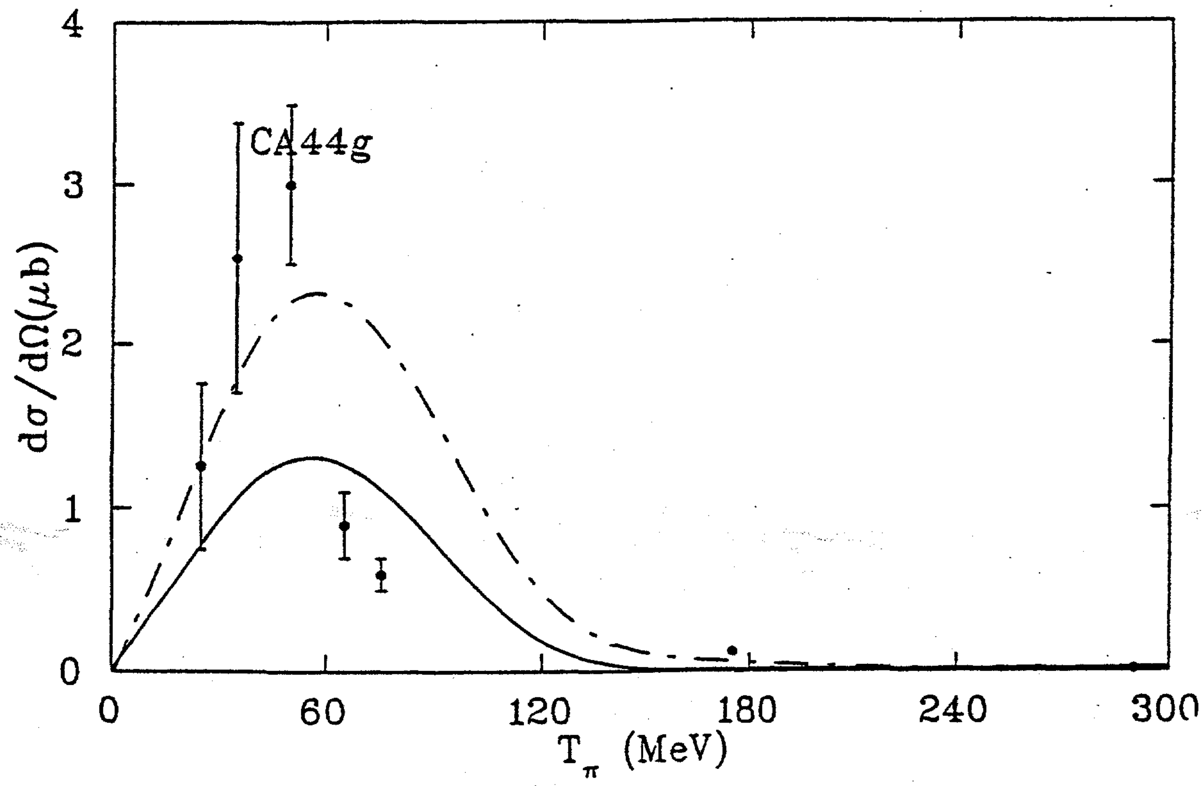

Figure 2.6: Pion double charge exchange at forward angles on ^{44}Ca leading to the ground state

is the range of the off-shell t-matrix. For technical reasons it is somewhat difficult to calculate with a range larger than about 500 MeV/c. For this reason most of our previous calculations were made with values in this range. More modern estimates of this quantity put it in the range of 600-800 MeV/c or even higher.

We have recently performed calculations to see if some of these difficulties can be overcome. For the fourth point we have improved the numerics of the calculation to the point that calculations with an off-shell range of 800 MeV/c are reasonably accurate (1%). For the propagation of the intermediate pion we use the same optical model as for the external legs and we simply show the results for no Gamow-Teller states or full strength for these states. The true results can be expected to lie somewhere in between depending on our understanding of the reason for (and the degree of) the quenching. For the nuclear wave functions we take what is available and would prefer the simple wave functions if possible. For example, the ground state transitions in ^{44}Ca and ^{48}Ca are taken only from the $f_{7/2}$ shell and do not have an "A" amplitude[12] hence are the simplest. For the first problem with the δ-function, we continue to calculate with it included for the moment.

Some of our results are summarized in Figures 2.5 and 2.6. In the case of double charge exchange to the analog (and ground) state in ^{58}Ni we see that the resonance peak is very strong indeed if no double spin flip is included. For the ground-state transition in ^{44}Ca the agreement with the data is quite good. The same holds for ^{48}Ca. For the analog transitions the peak is clearly present in the data and the calculations but, since the peak in the "A" amplitude is at a slightly different energy than that in the "B" amplitude (because of the δ-function?) the total peak is shifted.

For ^{18}O the results are particularly interesting. In this case there are *two* peaks observed experimentally, the second one around 110 MeV. It is difficult to see why a second dibaryon would suddenly appear at this point. In our calculation the nuclear wave function is such that a second peak is also seen. The two peaks do not appear at the correct energies however (although they do have about the right spacing).

Our studies of this reaction are continuing but we are reluctant to see evidence for a dibaryon in this peak, even though we are not always able to fit the data perfectly.

This work is being done in collaboration with M. Elghossain and W. B. Kaufmann.

2.4 Pion Absorption in Nuclei

In order to understand reactions in which several nucleons result from the absorption process, the Large Angle Detector and Spectrometer (LADS) was constructed at PSI. The data is now becoming available and I am participating in its analysis, in particular comparing the 3 proton events to IntraNuclear Cascade (INC) calculations.

Attempts to correlate the amount of cross section attributable to two *observed* nucleons with that of the total measured absorption cross section indicated that a significant fraction was unexplained and apparently had to be attributed to "multi-nucleon" absorption. Such an observation is potentially very important since it would indicate a many-body mechanism for the conversion of mass to energy in, at least in this case. The difficulty is in trying to firmly establish the existence of this fraction of multi-nucleon absorption (distinguish it from "initial-state"(ISI) and "final-state" (FSI) interactions of the hadrons) and document its properties. Since the initial- and final-state interactions are defined to be on shell (otherwise how can one distinguish many-body from two-body reactions with ISI or FSI) they can be modeled with a classical collision code. There is one caveat, however, in this approach and that is that the wave properties of the pion propagation may need to be treated correctly.

While the INC which has been in use for several years (for the prediction of a number of reactions) is still currently being employed, a new version has been developed. In this new technique the nucleon-nucleon interactions are followed as a function of time in an "exact" solution of the classical many-body problem. Thus the final state interactions are handled by means of potentials (the Malfliet-Tjon potentials are used in practice). This technique allows clusters to be formed and leave the nucleus.

we are currently studying the case of pion absorption in ^{4}He. We observe bound states of two nucleons as final products and are classifying their energies and other physical properties. As a preliminary result we find that these "deuterons" are largely the spectators in two-nucleon absorption but there are some which have high energies and come from pick-up or other final-state interactions. It is too early to know if this model has enough overlap with physical reality to be of direct utility.

This work is being done in collaboration with the NMSU LADS experimental group.

2.5 Quantum Effects in Inclusive Reactions

The solution of the many-body Schrödinger equation for scattering problems is difficult indeed. One approach might be to consider all possible results arising from the initial conditions weighted equally and then calculate the quantum mechanical probability of each event. This would be an extremely inefficient procedure, however, since the dominant fraction of the events, if chosen randomly, would lead to very small probability and most of the calculational time would be wasted. A far more efficient procedure would be to choose the events according to some well defined probabilistic rule that gives an approximate representation of the process and then correct the approximate rule by taking for the weight of the event the ratio of the quantum probability to that of the model. This is a standard technique in Monte Carlo procedures known as importance sampling. The approximate event generator must have the property that it can be sampled and that the probability for a given event can be calculated. For this we will take a classical simulation in the form of the INC described above. The one we are using is known to give good results for simple reactions such as quasi-elastic scattering[2]. Deviations from the model are also seen and one is never sure if these discrepancies should be ascribed to new physics or to the fact the model is purely classical.

To start with we are treating a very simple case, that of pion charge exchange on the deuteron. The quantum correction we wish to consider is due to quantum vs. classical double scattering. One might think that the double scattering contribution to this reaction is small and that is, in general, true. However, for the cases in which just one charge exchange on the neutron takes place (without a scattering from the other nucleon) the spectator proton has very low energy in the final state, due to the low Fermi momentum of the deuteron. In a recent LADS experiment the two protons were detected with a minimum energy of 15 MeV. Under these conditions the double scattering contribution is dominant. However, the single scattering is large enough that it must be considered. A number of separate types of coherence effects have recently been calculated.

This work is being done in collaboration with J.-P. Dedonder.

2.6 Pion Scattering from Polarized Nuclei

Recent calculations have been made for pion scattering from polarized ^{3}He to be compared with data soon to be available from LAMPF. Calculations are under way for the charge exchange reaction from polarized ^{3}He. It is hoped that this second experiment will be scheduled this summer and will serve as a thesis project for one of the students in experimental physics, Qihua Zhao, who is actually performing most of the calculations.

Chapter 3

Personnel

The Principal Investigator on this grant is William R. Gibbs.
Since January 1993 one graduate student, Li Ai, has been participating in the research effort and supported by the grant.

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