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DOE/ER/40740--T1

The Theory of Hadronic Systems
Annual Progress Report
DOE Grant No. DE-FG03-92ER40740
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April 12, 1993

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Budget removed

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Introduction

This report summarizes the work on theoretical research in the area of the hadronic interaction carried out at New Mexico State University in 1992-1993 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 *motif* in all 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.

Research Summary

2.1 Isospin Breaking in the Pion-Nucleon System

The study of a classification of isospin breaking in the pion-nucleon sytem was recently completed and published[1]. This work was done in collaboration with W. B. Kaufmann who, in fact, took the primary role in its development and publication. To our knowledge no such classification had previously been made. Such a formalism is essential in order to distinguish the different types of isospin breaking and determine which experiments need to be performed in order to completely specify the system. The classification of these effects takes the form of a tensorial ranking in isospin operators with certain ranks (and specific operators) being associated with given physical origins. For example, $\rho - \omega$ mixing has a different isospin-breaking character, in the pion-nucleon interaction, than $\pi - \eta$ mixing. The two effects can be separated experimentally (at least in principle).

In current work along the same lines (with W. B. Kaufmann and Mohini Rawool-Sullivan) a study is nearing completion analyzing the experimental evidence for isospin breaking in the πN system. Most evidence for such breaking is negative, in the measurements which have been made to date, except for pion-deuteron scattering. The total cross section measurements made by Pedroni *et al.*[9]on deuterium, using positive and negative pion beams, show a clear difference in the two cross sections. This difference has traditionally been 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. We see no reason to question this interpretation. There also exist measurements of the differential cross section for pion scattering from deuterium (made at TRIUMF, LAMPF and Saturne) which give information on isospin breaking. While interpretations given in the paper by G. Smith *et al.*[10] on the published measurements at TRIUMF appear to disagree with the results of Pedroni, we find a very reasonable agreement between the two sets of measurements. In fact, we can extract a value of the quark mass difference from the 180 MeV differential data alone which agrees within errors with that extracted from the Pedroni data. While π-d data address only one of the six possible isospin breaking amplitudes, a test of $\rho - \omega$ mixing is none the less possible since this source of isospin breaking contributes to this amplitude. We find that the new (and partially unpublished)[11] low-energy data on the charge asymmetry in pion-deuteron scattering are consistent with the effects of the Coulomb interaction and quark mass differences only. The addition of charge-symmetry breaking due to $\rho - \omega$ mixing, using the same parameters needed to explain the isospin breaking observed in the nucleon-nucleon system[12], results in a significant discrepancy between theory and data. A natural first interpretation of this result is that $\rho - \omega$ mixing is *not* the major cause of isospin breaking in the nucleon-nucleon system, as has generally been believed. We await the investigation of other possible explanations for this discrepancy.

While the principal task of the above work is to classify the isospin breaking in the pion-nucleon system, tabulate the present estimates of the breaking parameters and suggest a set of experiments which are most likely to lay its structure bare, we also point out that the assumption of the non-existence of an isospin-breaking interaction of order $\Delta I = 3$ provides a relationship among the *widths* of the different charge states of the Δ (in contrast to the *masses* whose relations are well known) which apparently has not been noticed before. This analysis exists in rough-draft form and we expect to submit it for publication in the summer of 1993.

2.2 Direct Capture of Pions into Deeply Bound Atomic States

The strong interaction of a pion with nuclear material can be studied by means of the measurement of the energy shifts and the non-electromagnetic contributions to the widths of pionic atoms. The effect of the pion-nucleus interaction is stronger the closer the pion is to the nucleus, and hence the higher the atomic number. One advantage for this method of studying scattering is that the pion is in a definite atomic orbital, hence has a single, well-determined, angular momentum with respect to the nucleus. Unfortunately the normal capture mechanism is very inefficient for populating deeply bound states since in the process of the cascade after initial capture in a high orbital state, the pion is more likely to be absorbed by the nucleus than to "descend" to the next orbital. The lowest s-wave orbital cannot be seen in nuclei much heavier than Z=10. Many possible reactions have been considered for populating these tightly bound states but there is no decisive evidence that any such deeply bound state has been seen. W. B. Kaufmann, P. B. Siegel and I have considered the reaction where an incident negative pion impinges on a nucleus and knocks out a proton from an outer nuclear shell, at the same time being captured in an atomic orbital. While the momentum transfer might seem, at first glance, to be too large to be supported by an atomic orbit, the Fermi momentum of the proton can largely compensate for this seeming default. In fact this larger momentrum transfer is often an advantage since many of the shells in heavy nuclei have moderately large angular momenta and thus an appreciable angular momentum (and hence momentum) transfer is necessary to reach a pionic state with samll ℓ. The cross sections are not unreasonably small but the backgrounds are estimated to be large. A feasibility study was undertaken to measure these backgrounds and an experiment with high resolution could be mounted to measure the properties of these states.

2.3 Knock Out of Secondary Components in the Nucleus

The subject of quasifree knock out is of interest in the study of the hadronic interaction because it allows the possibility of the study of the projectile-nucleon interaction in a nuclear environment. However the degree to which the scattering takes place from a single nucleon (and not, for example, from the other A–1 nucleons in whatever excited state the conglomerate happens to exist) is not clear. The use of pion "quasifree" scattering from a "proton" in ^{4}He offers unique insight into this situation. In this case it is possible to measure the exclusive final state in which the proton and triton are both in their ground state. By chosing the charges of the pion, the scattering from the proton or the triton can be selected to be dominant. Indeed studies over a complete angular range indicate that the ratio

$$\frac{\sigma^+(\theta) - \sigma^-(\theta)}{\sigma^+(\theta) + \sigma^-(\theta)},$$

where the + or - indicates a π^+ or π^- beam, shows a large positive excursion in the angular region of quasifree proton scattering and a large negative excursion in the region of quasifree triton knock out. Calculations consisting of the coherent sum of the two knock-out reactions reproduce the qualitative features of the data. The addition of a "shadowing" correction in the form of double scattering improves the agreement but clearly additional physics is needed.

These results, the measurements and some discussion of the missing physics were recently published in Physical Review Letters [3]

2.4 Study of the Radii of Neutron Distributions in Nuclei

The understanding of neutron distributions in nuclei is one of the most important problems in nuclear structure. While electron scattering does an excellent job of determining the charge density, and the proton distribution can be reasonably infered from these charge distributions, the densities of the (more numerous) neutrons are poorly known. This knowledge is more than just determining the "other half" of the nucleon distributions. Neutrons are the excess particles (the valence particles in many pictures) and in the case of the calcium isotopes studied here there can be zero to eight neutrons outside of a closed shell.

In this case the degree to which nucleons interact with each other, rather than the central core, can be examined. Such studies are at the heart of the usual approximations used in calculating nuclear structure. In a recently published analysis[4] J.-P. Dedonder and I applied pion multiple scattering theory to the analysis of pion scattering data by Boyer *et al.*[13] to make a determination of the absolute total neutron radii to an accuracy of the order of 1%, an error about a factor of 3 smaller than any previous determination.

The valence neutrons in ^{42}Ca are found to have a radius significantly larger than those of ^{44}Ca which are, in turn, somewhat larger than those of ^{48}Ca. The densities of the valence neutrons are shown in Figure 2.1.

One interpretation of this result is that since the two neutrons in ^{42}Ca are highly correlated with each other, due to the necessity of coupling the two $f_{\frac{7}{2}}$ neutrons to spin zero, they interact strongly and a larger fraction of the binding energy of the system of the last two neutrons is due to the neutron-neutron interaction and less due to the neutron-core interaction than in the case of the other isotopes which have a progressively smaller correlation among the neutrons. For ^{48}Ca, since the wave function is represented by a Slater determinant, the neutrons are highly anticorrelated, *i.e.* as far away from each other as possible, leading to a stronger interaction with the core and a smaller radius. This observation provides a partial understanding of why the proton radius of ^{48}Ca is observed to be not larger than the proton radius of ^{40}Ca but about the same size. The proton radius does not grow throughout the shell because the valence neutron radius is shrinking.

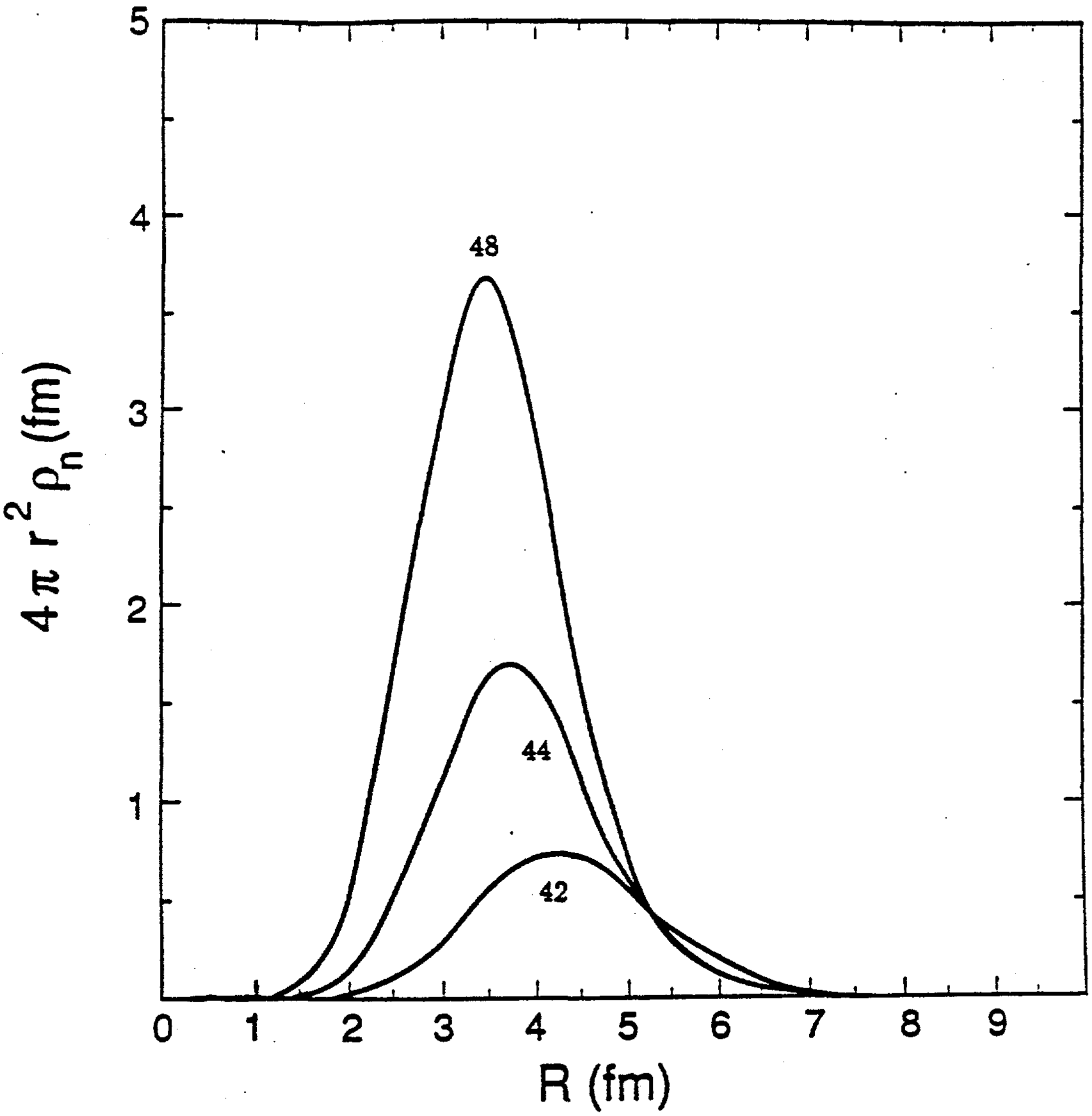

Figure 2.1: Valence neutron densities (multiplied by r^2) infered in the present work. The shift in the radius toward smaller values with increasing mass number is clearly seen. Most calculations assume that this radius remains constant.

2.5 The Hadronic Double Scattering Operator

In a previously published paper we[14] showed that, due to the simple nuclear structure of the calcium isotopes, the double charge exchange operator can be separated into a long- and short-range part, the range in question being the distance between the two neutrons on which the charge exchanges take place. This separation of ranges takes place, however, in terms of nuclear matrix elements of the fundamental operator. In the recent study [5] we undertook the investigation of the simplest form of the pion double scatttering operator, *i.e.* neglecting the effect of the nucleus which binds the two neutrons on the initial, final and intermediate pion. Even in this very simplified version of the operator certain general features can be discerned. Among these are the cancellation between the non-spin-flip and double-spin-flip parts of the interaction, the separation into 3 distinct zones corresponding to ranges of the operator and the relationship to the classical cross section for double scattering. Some comparison with the one-pion-exchange part of the nucleon-nucleon interaction is made, in particular the effect of the removal of the δ-function.

2.6 Transparency in Pion Production

The study of reactions initiated by pion beams of the order of 500 MeV kinetic energy leads to some very interesting results. This is the energy at which pion production (by pions) begins to become important. In fact the low energy portion of the pion spectrum resulting from such beams is dominated by pions that were produced rather than those which underwent large-energy-loss scatterings. These produced pions have an average energy of about 180 MeV or very near the Δ_{33} energy. Since the mean free path of the 500 MeV incident energy pions is long, the produced pions are created well within the nuclear volume which means that they must traverse a significant amount of nuclear material to escape. Thus, in the spectrum of pions produced, one expects to see a minimum in the region of the 33 resonance corresponding to the fact that pions produced in that energy region are either re-absorbed or scattered to lower energies. In fact no such minimum is observed in the data. Comparisons with an IntraNuclear Cascade code reveal a difference of an order of magnitude in this energy region. Attempts to eliminate this large discrepancy with corrections to the production mechanism or with correlations among initial nucleons have little effect.

The only way that has been found to obtain reasonable agreement with the data is to allow essentially all *produced* pions to escape the nucleus without interaction. Eliminating the second interactions of *all* pions leads to a very poor agreement with the data; it seems to be only the produced pions which escape the nucleus.

This work has been written up[6] and submitted to Physical Review Letters.

2.7 Asymmetry in Pion Scattering and Charge Exchange from Polarized Nuclei

In the study of the hadronic interaction the spin degree of freedom has always proved to be crucial. For scattering of pions from nuclei, since the pion itself has no spin, the additional handle on the understanding on the interaction must be provided by the polarization of the nucleus itself. Only recently have experiments on polarized nuclei been performed and the results have been poorly reproduced by theories up until now. Peter Siegel and I have recently undertaken an analysis of the data on elastic scattering, charge exchange and (to a lesser extent) inelastic scattering. The results [8] of this study comparing with data[15, 16] will be submitted shortly for publication in Physical Review.

In this first cut we restrict ourselves to reactions on spin 1/2 nuclei (although we have done some work on higher spins). We find for ^{13}C that the data on elastic scattering and charge exchange is well understood with the exception of certain forward angle points (see figure 2.2). For elastic scattering from ^{15}N[17] we find an improved agreement with the data over previous calculations[18] but the theoretical asymmetry is still somewhat too large (see figure 2.3).

Included in the study is a comparison of the optical model approach used by one other theoretical group and the distorted wave impulse approxmation that we have employed. A short critique of the two methods is given. We also give a discussion of how the relative phases of the amplitudes are related to the underlying potentials to give a physics insight into the polarization asymmetry.

2.8 The Mechanism of Pion Absorption in Nuclei

While the concept of the equivalence of mass and energy was introduced at the beginning of this century and the conversion between the two is commonplace in modern physics, our understanding of how this transformation actually takes place is minimal. It would seem that it involves a quark-antiquark annihilation in the case of the conversion of the pion mass to pure kinetic energy in a nucleus but how does the reaction take place?

Pion absorption on one nucleon cannot occur in free space due to the conservation of energy and momentum and even in a nuclear medium the missing momentum must be supplied by the Fermi motion. Since the momentum needed is of the order of 500 MeV/c the cross section for this one-nucleon process is very small.

In the case of two nucleons the extra momentum can be shared in an equal and opposite manner by the two final nucleons and the absorption on the deuteron is well measured and moderately well understood[19]. Since two nucleons are all that are needed to "solve" the momentum problem it was generally assumed that even in a nuclear environment, where there many nucleons around, the absorption takes place on a pair of nucleons.

Attempts to correlate the amount of cross section attributable to two *observed* nucleons with that of the total measured absorption cross section[20] 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

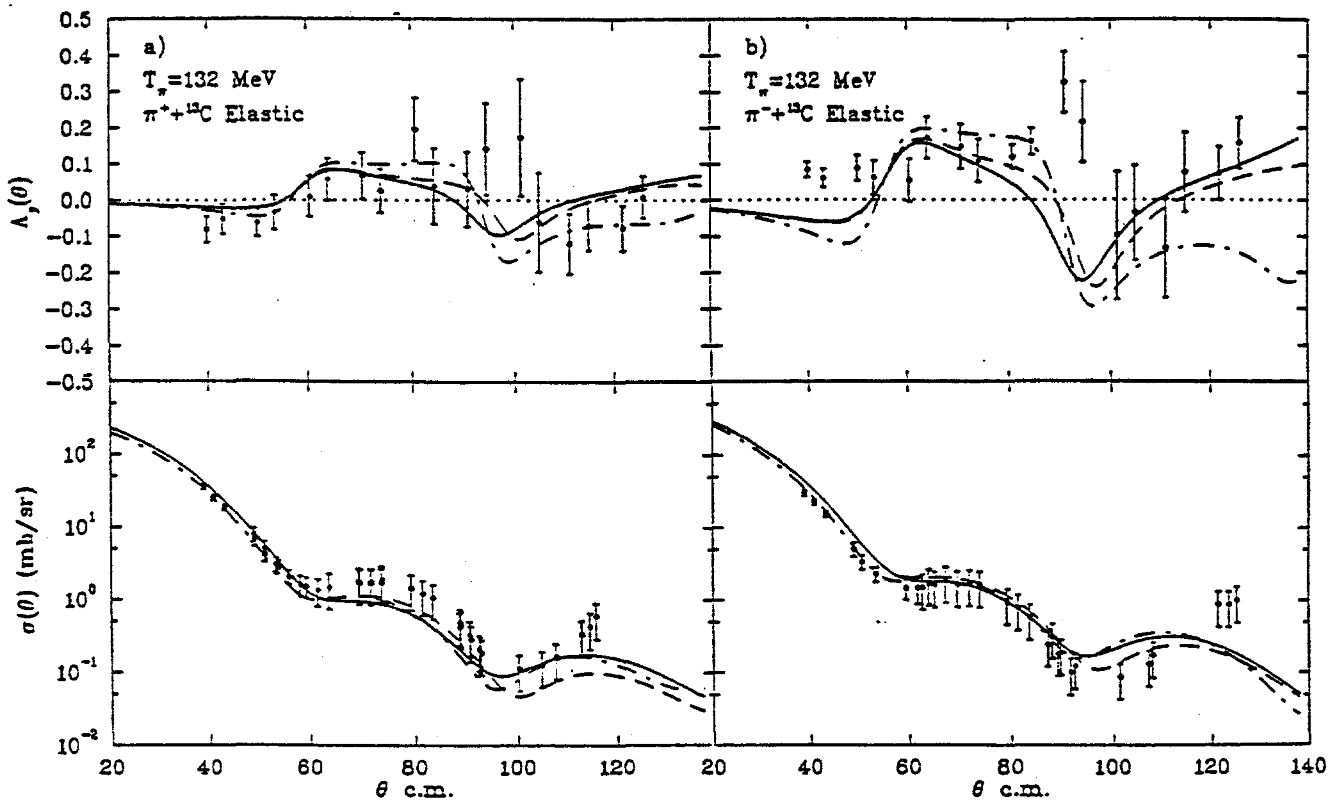

Figure 2.2: Comparison of theory and experiment for asymmetry and differential cross sections at 132 MeV for elastic scattering from ^{13}C. The difference in magnitude of the two charge of pion is clearly seen in both the theory and data. The solid line is the result obtained from distorted waves computed with the pure first-order optical potential and the dashed line is the result obtained by adding an imaginary potential proportional to "ρ^2" to the optical potential to account for true pion absorption.

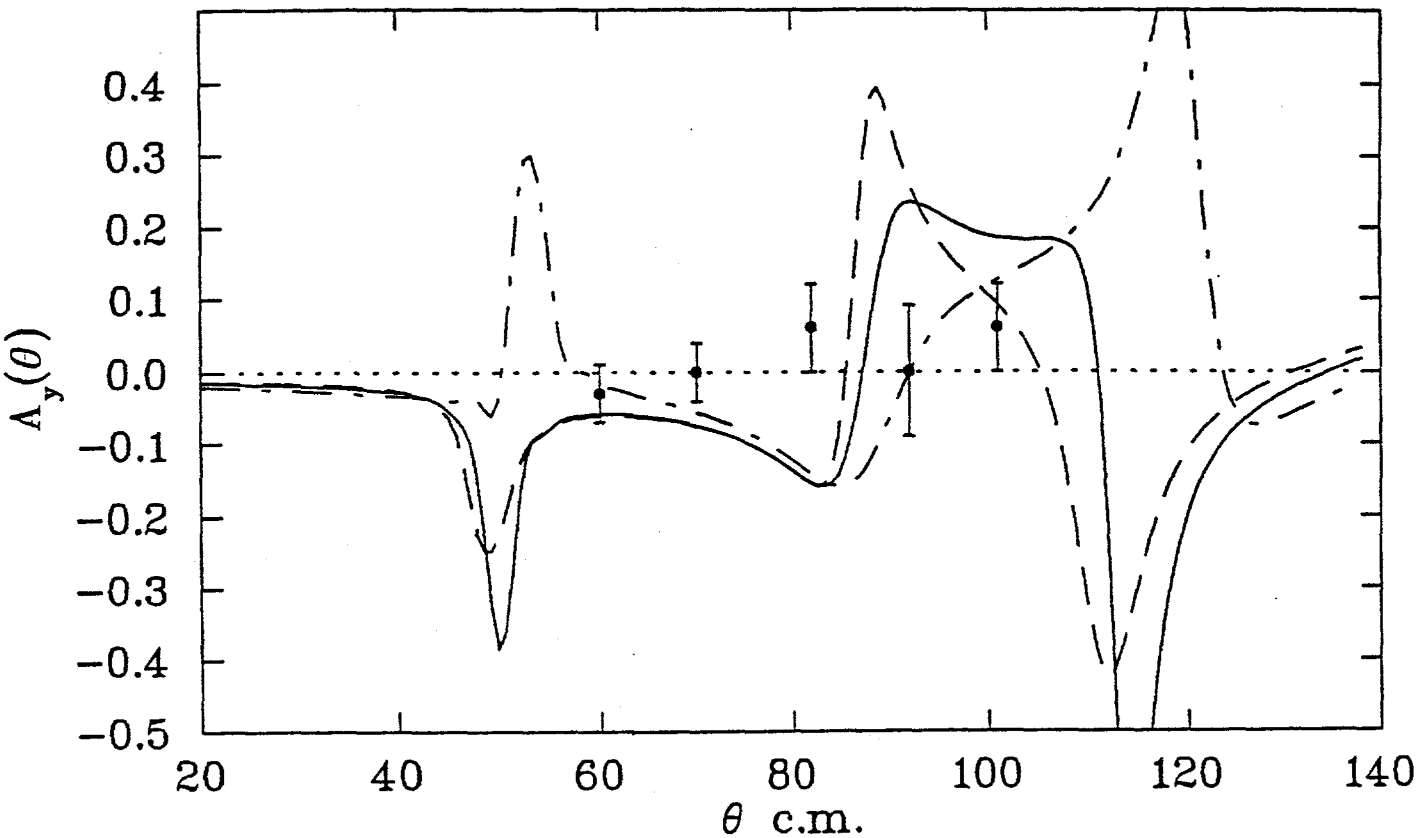

Figure 2.3: Comparison of theory and experiment (at 164 MeV) for the asymmetry in pion elastic scattering from ^{15}N. Theoretical curves are shown at 150 MeV (dash-dot), 164 MeV (solid) and 170 MeV (dash) to show the change in character of the asymmetry at the resonance (at least in the theory) and to give an idea of the sensitivity to small energy shifts. The agreement is satisfactory, within errors, except for the point at $\theta = 82°$.

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.

In order to understand these 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 Casade calculations.

2.9 The Neutron-Proton Charge-Exchange Reaction

Neutron-proton charge exchange at zero degrees (*i.e.* np scattering at 180 degrees) shows a sharp peak in the differential cross section. 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 the $\ell = 0$ component is large (non-unitary in fact) and negative while all other contributions are positive. Removing the s-wave component leads to a cross section of about the right size. A number of authors have considered various ways of suppressing the short range contribution to the amplitude but each of them has some problem (usually they are energy dependent). Benoit Loiseau and I 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 it is done in the context of pion exchange between the quarks which make up the nucleon. We recently found that this same proceedure gives a good qualitative representation of the spin-transfer properties of the n-p charge exchange reaction when compared with recent data from LAMPF [21]. We are currently studying what additional short-range potentials are necessary to obtain quantitative agreement with the data.

We also are considering the effect of these types of representation on the results one might find in a nuclear medium. Clearly there is a possible relation of this study to the problem of the "missing" Gamow-Teller strength in the nucleus.

2.10 Modification of the Fundamental Structure of Nucleons in Nuclei

We suggested a few years ago[22] that a possible way to study the modifications of the structure of the nucleon in a nuclear environment is to compare the total cross section of K^+-nucleus scattering with K^+-d scattering. Since 90% of the total cross section is given by single scattering this ratio will be sensitive to any changes in the K^+-nucleon interaction in the nucleus. In the naive quark model one can show that a simple relationship exists between the confinement range and the s-wave phase shift so that if an increase in size of the nucleon occurs in the nucleus, as suggested by Close, Roberts and Ross [23], then the ratio of total cross sections should be larger than that expected from multiple scattering calculations using only standard medium modifications. These measurements have now been made[24] and indeed there does seem to be a renormalization of about the size expected with a definite discrepancy from the fiducial calculation indicated.

The energy dependence seen in the measurements is somewhat different from that predicted originally although those calculations were only meant to be indicative of the size of the effect. Our next task is to investigate the results and evaluate the experimental dependence on energy and mass number obtained.

2.11 Antiproton Annihilation in Nuclei

In 1984 D. Strottman and I suggested[25] that the use of energetic antiprotons would provide a useful technique for creating high energy densities within the nucleus. An experiment based on our calculations (and those subsequently done by myself and J. Kruk) was proposed by a Rice-BNL collaboration at Brookhaven National Laboratory. The data have been taken and I am participating in its interpretation. As a first stage the charged-particle multiplicities have been extracted and compared with our calculation. They are consistent with the prediction of the IntraNuclear Cascade code with *no* hadronization time, apparently in contradiction to "conventional wisdom".

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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