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STRONG INTERACTION PHYSICS WITH PIONS AT LAMPF

Report of the Study Group on Future Opportunities at LAMPF

Editors

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PREFACE

In preparation for the Nuclear Science Advisory Council (NSAC) 1995 Long-Range Plan, the Board of Directors (BOD) of the LAMPF Users Group initiated a study of the near-term prospects for nuclear and particle physics at LAMPF following the termination of funding as a national user facility. A Study Group with broad representation of the nuclear and particle physics community was formed to consider future opportunities in pion, muon, neutrino, and neutron physics under the assumptions that (1) cost-effective experimental activity would be possible at LAMPF as a result of continuing high-intensity operation of the accelerator under sponsorship of the defense-programs branch of the DOE; and (2) the DOE nuclear physics program would support high-priority experiments on a case-by-case basis. Based on the conclusions of the Study Group, a LAMPF Users Group White Paper was prepared and submitted to NSAC.

Pion physics underwent the most extensive examination due to the fact that it has traditionally been the most active experimental area. The first stage of this process was the Study Group Report on Strong Interaction Physics with Pions at LAMPF, intended as a "snapshot" of the current interests of the LAMPF pion-physics community. This report is presented in an updated form as the current document.

After an evaluation of the material collected, the highest-priority experiments in pion physics were identified and highlighted in the White Paper. The section "Strong Interaction Physics with Pions at LAMPF" is reproduced in the appendix of the present document.

The basis of the Report consisted of one-page proposals received in response to solicitation from the LAMPF User community. Contributions were received from the following individuals: J. Amann, R. Boudrie, G. Burleson, J. Comfort, D. Dehnhard, G. Glass, A. Hayes, B. Holstein, J. Matthews, C. Morris, E. Pasyuk, R. J. Peterson, D. Pocanic, R. Ristinen, K. Seth, S. Sterbenz, H. A. Thiessen, and J. Zumbro. Many others provided input in less explicit format, including participants in the Pion Physics Study Group that met regularly at LAMPF during the spring and summer of 1994, speakers at the August 1994 meeting of the LAMPF Users Group, members of the Study Group, members of the pion physics community who attended the open discussion at the November 1994 LAMPF Program Advisory Committee meeting, and members of the user community who communicated their critiques after the Report was widely circulated by electronic mail in mid-December 1994. Based on the comments received, a draft of the contribution to the White Paper was proposed and refined later using input from discussions at the LAMPF Users Group Workshop, which was held in Los Alamos on January 22, 1995.

As the intention of the Report was to reflect the interest of the users, the material has been left largely in the words of the individual contributors, i.e., no attempt has been made to impose a uniform compositional style. However, in the editing process, an effort has been made to provide some continuity between the contributions, and to expand or abridge as appropriate.

Mikkel B. Johnson and June L. Matthews, Editors
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I. INTRODUCTION

The LAMPF accelerator, with its high-intensity beams of pions and array of high-resolution spectrometers, provides unique opportunities for experimental investigations of nuclear phenomena embracing traditional issues of nuclear structure as well as fundamental issues of strong-interaction hadron dynamics. During the operation of LAMPF as a national users facility, Nuclear Physics has undergone an evolution in the way it pictures nuclei: from a system of nucleons interacting through potentials to a system of mutually coupled nucleons, $\Delta(1232)$'s, and mesons. While nuclear physics is in the midst of yet another shift of paradigm, with quarks and gluons playing a central role, the traditional picture still has great predictive power, and therefore LAMPF has new opportunities to contribute to solving problems of current interest. At the same time, LAMPF is poised to make important contributions to the evolving area of nonperturbative QCD, where we will be learning how to connect phenomena at large momentum transfer ("condensates" of quarks and gluons) to those at lower momentum scales where the physically observable hadrons are the natural degrees of freedom.

Within the traditional area, exploration of nuclei having extreme ratios of neutron/proton number is of growing interest in a variety of contexts, including astrophysics. Pion double charge exchange (the $(\pi^{\pm}, \pi^{\mp})$ processes) can produce proton-rich nuclei such as ^{9}C, ^{10}C, and ^{11}N as well as neutron-rich nuclei such as ^{10}He, ^{11}Li, ^{14}Be, and ^{17}B. With spectrometers available for analyzing the outgoing pion spectra, one can study interesting and controversial modes of motion (soft-dipole modes) and obtain angular distributions that explore the spatial extent of neutron halos. The unique properties of the single charge exchange reaction $(\pi^{\pm}, \pi^{0})$ make pions an important tool for exploring shape differences of neutron and proton distributions in heavy nuclei, an activity that led to the formulation of F-spin symmetry breaking in the interacting boson model.

Looking toward the future, the exploration of Quantum Chromodynamics (QCD) is a task being taken up to an increasing extent by theoretical as well as experimental nuclear physicists. The investigation of perturbative QCD relies crucially on energetic hadron and electron facilities with beams in the multi-GeV range. However, study of nonperturbative QCD requires low-momentum transfer (of scale $\Lambda_{QCD} \sim 500$ MeV), which is the domain of meson factories and other medium-energy accelerators. Such facilities create simple few-quark systems (mesons, baryon resonances), which experience has shown generate rich opportunities to investigate hadron dynamics using the nucleus as a laboratory. The gradual shift of paradigm in nuclear physics is leading to new interpretations of familiar phenomena that will increasingly lead to fresh ideas for experiments in this energy domain. Examples include precision measurements of elementary cross sections, exploration of hadron dynamics in the nuclear medium, and dibaryon searches. Such experiments increasingly rely on coincidence measurements that require the intense beams, and the use of ingenious methods including polarized (i.e., spin-oriented) targets. Dynamics of higher-mass mesons and baryon resonances, including those with strange quarks, are an integral part of this effort, and they may be produced at modest cost and effort by accelerating secondary beams to high energy and high intensity using innovative superconducting cavity technology.

II. π-NUCLEON AND π-π SCATTERING

The holy grail of particle and nuclear physics for the past two decades has been to confirm the validity of QCD as the basis of hadron dynamics. Until recently this goal has been thwarted by the inherent nonlinearity of the theory. However, the evolution of techniques based on (broken) chiral symmetry has allowed the generation of various low-energy theorems, which provide precision tests of QCD. LAMPF provides high-intensity beams of pions, which enter as the Goldstone boson of spontaneously broken chiral symmetry. Because the pion is a central feature of the chiral Lagrangian, a model-independent representation of QCD in terms of physically observable states, it can be exploited to explore fundamental issues, such as chiral symmetry and its breaking, in basic scattering processes including pion-nucleon and pion pion scattering.

A. Pion-Nucleon Scattering

Even though the meson factories have now been in operation for more than twenty years, our empirical knowledge of the pion-nucleon interaction is still surprisingly imperfect. Recent work at LAMPF, TRIUMF, and PSI has revealed discrepancies between pre-meson-factory and newer data of as large as twenty percent, of the order of ten standard deviations. We have a clear opportunity now to make a fundamental contribution to strong-interaction physics by establishing a reliable database of cross sections in the energy region up to and including the first resonance.

The fundamental nature of the measurements is reflected by the importance of the quantities they establish. One of these is the value of the pion-nucleon coupling constant, which had been accepted as being well known for years to an accuracy of about 1%, but which now is uncertain by about 5%. Another is the sigma term, derived from pion scattering data, and related to the possible strange quark content of the nucleon. Sophisticated arguments based on (what we now know to be) an inaccurate database have suggested that as much as 20% of the nucleon mass may be due to strange quarks. Other arguments suggest a value much closer to zero. Tests of chiral symmetry breaking and isospin symmetry also follow from pion-nucleon scattering data.

In connection with issues of isospin symmetry, recent work [1] has explored the topic of charge independence in πN scattering. Strong evidence for a discrepancy of the order of 7% beyond the contributions of the $\pi^{\pm}p$ Coulomb interaction and the hadronic mass differences are suggested by this study. Such a claim undermines previous analyses of the sigma term. A proper evaluation of the claim and an understanding of its implications for this and other issues can only be made by resolving existing discrepancies in the πN database and by expanding this base with high-quality data on new observables.

LAMPF is the best available facility for testing many of these points of vital interest to nuclear and particle physics. It has the highest energy pion beam of any of the three meson factories and the highest pion beam intensity. LAMPF has recently developed a neutral meson spectrometer, the only one capable of performing some of the required measurements. The laboratory also has the capability of providing cryogenic hydrogen targets, both polarized and non-polarized. Three measurements of the pion-nucleon interaction that would lead to significant improvement in our knowledge of this fundamental topic and that are well-matched to the beams and spectrometers at LAMPF are mentioned below.

1. Analyzing Power for the $\pi^- p \rightarrow \pi^0 n$ Reaction; (LAMPF Experiment 1178)

This experiment will measure polarization asymmetries for the charge exchange reaction in the energy range 45–190 MeV, where such data do not exist. The measurements will be made with a polarized hydrogen target similar to that used for previous LAMPF experiments. The new Neutral Meson Spectrometer will detect the gamma rays from π^0 decay. In combination with cross section data, the asymmetry measurements will provide important information on the relative phases between the spin-independent and spin-dependent terms in the effective pion-nucleon interaction. Data at the lower energy range of this proposal are very sensitive to small changes in the P_{11} phase.

This proposal is directed to the needs of modern phase-shift analyses of pion-nucleon scattering data [2] and to the goals in Ref. [1]. Results will also be useful for constraining extrapolations of the πN amplitudes to zero energy for extraction of the sigma term.

2. $\pi^\pm \vec{p}$ Analyzing Powers at 45 and 67 MeV; (LAMPF Experiment 1256)

This experiment will measure the angular distributions of the analyzing powers for $\pi^\pm$ scattering from polarized protons at 45 and 67 MeV. The experiment is proposed for the LAMPF LEP channel and will use techniques that were perfected in earlier measurements of pion scattering on polarized ^{13}C. No measurements of the analyzing power for elastic scattering have been published at energies below 98 MeV.

At the lower energies, existing cross-section data from several laboratories have numerous inconsistencies. The analyzing power measurements have much greater sensitivity to small changes in the phases of the partial wave amplitudes, and they thus provide a definitive test of the low-energy elastic cross section data that are at the center of hot dispute. They are also, by their nature, relatively immune to errors of normalization. Most of the sources of systematic error experienced in cross-section measurements vanish in these measurements; the remaining errors are under control and should lead to an uncertainty in the analyzing power of no more than about 2%.

By helping to establish a reliable set of phase shifts that contribute importantly at these low energies, the proper πN amplitudes can be extrapolated to the Cheng-Dashen point with reduced uncertainty. This extrapolation leads to the sigma term and determination of the strange quark content of the nucleon; uncertainty in the low-energy πN phase shifts is now the dominant error in this extrapolation. They also are central to the discussion of charge independence in πN scattering [1] outlined above. The measurements thus impact the determination of several fundamental quantities in strong-interaction physics.

In view of the history of difficulties that have plagued πN cross section measurements at low energies, and the significance of the analyzing power measurements, it is important for these experiments to be carried out at all of the meson factories. Coordinated activities are under way at PSI and TRIUMF.

3. E2/M1 Ratio in the ($\Delta(1232) \rightarrow$ Nucleon) Electromagnetic Transition

The pion radiative capture process can provide critical information on the π-nucleon interaction as well as on the structure of the nucleon and its excited states, such as the $\Delta(1232)$. If the nucleon and $\Delta(1232)$ are spherical in shape, the electromagnetic transition between them will be pure M1. Various theoretical models, based on QCD or other formulations, predict non-spherical components that must lead to E2 (and C2) components. Several experiments at LEGS, Bates, Bonn, Mainz, and CEBAF are pursuing this question through electromagnetic excitation of the proton to the $\Delta(1232)$. Whereas the electron scattering reactions are sensitive to both the C2 and E2 components, the inverse reaction $p(\pi^-,\gamma)n$ is sensitive only to the E2 components. It thus provides an independent constraint on the electromagnetic data.

4. Coulomb-Nuclear Interference in $\pi^{\pm}p$ Elastic Scattering

The proposed study follows from two very recent papers by Gerhard Höhler [3,4]. Höhler makes the point that far-forward (near $t = 0$) differential cross section data in the Coulomb-nuclear interference region are needed at energies in the range of the LAMPF P^3 channel. The experiment gives the total cross sections (and the real parts of the scattering amplitude at $t = 0$), which are needed for an improved determination of an important subtraction constant in the forward dispersion relation. LAMPF is the facility of choice for this measurement because of the broad energy range of pion beams at a single channel. The experiment is not possible at PSI or TRIUMF.

We propose an arrangement at the P^3 channel that is similar to the one of Ballion *et al.* [5]. Data will be taken at several energies from 60 to 550 MeV. Measurements must be made with highly accurate statistics, which can be readily obtained with the proposed setup. As with many experiments of such fundamental nature, the bulk of the time will be spent on checks of systematic uncertainties.

These results will overlap nicely with the π^+p work of Ref. [5], which had a lowest energy of 480 MeV for π^+, 870 MeV for π^-. At lower energies, measurements have been made in the Coulomb-nuclear interference region at PSI at 55 MeV by Wiedner *et al.*, [6] and at 32, 45, and 68 MeV by Joram *et al.* [7].

B. $\pi\pi$ Scattering

A particularly important and theoretically clean example of low-energy theorems constituting precision tests of QCD are those for $\pi\pi$ scattering, which include those written down by Weinberg nearly thirty years ago using current algebra/PCAC techniques. Presently available data agree with these predictions within the errors, which are in some cases substantial. Therefore, in order to fully test such predictions, one needs a new set of experiments. These must allow reliable extraction of the $\pi\pi$ amplitudes at the 5% level. A multi-pronged approach is essential.

At DAΦNE, data from KLOE on K_{e4} decays should measure the difference between S- and P-wave phases in the low-energy region. Planned measurements of the lifetime of $\pi^+\pi^-$ atoms should provide a precise measure of the scattering length difference $|a_0 - a_2|$. Additional information will require the use of pion beams. The $\pi\pi$ scattering amplitude at threshold is fully determined by the chiral symmetry breaking part of the interaction, i.e., in the chiral limit the scattering lengths vanish identically. To the extent that they differ from zero, $\pi\pi$ scattering lengths directly measure the chiral symmetry-breaking terms in the strong interaction Lagrangian, and have, consequently, been an object of study for over three decades. With the recent development of systematic approaches to building effective strong-interaction Lagrangians at low energies based on QCD, most notably Chiral Perturbation Theory, this subject has attracted considerable renewed attention.

Measurements of $\pi N \rightarrow \pi\pi N$ reactions in the threshold region have the potential for extraction of reliable S-wave scattering lengths, as pointed out many years ago by Olsson and Turner. The current experimental situation is reasonably good, although data of higher precision would be welcome. The primary challenge here is that a theoretically sound method that would allow extraction of the phase shifts is lacking. Full-kinematics $\pi N \rightarrow \pi\pi N$ data at energies of 300 MeV and higher, when fully analyzed by means of the Chew-Low technique, have the potential to yield precise low energy phases. Knowledge of such phases, besides providing a test of QCD, allows accurate evaluation of final-state interaction effects in (the host of) other processes that involve a $\pi\pi$ channel.

Both $I = 0$ and $I = 2$ $\pi\pi$ scattering lengths need to be determined more precisely. While the theoretically cleanest way to measure $a_0^0(\pi\pi)$, the isoscalar S-wave scattering length, involves K_{e4} decays, the most promising method for determining a_0^2 remains the model-independent Chew-Low analysis. Such analyses have been performed in the past on data sets obtained at relatively high pion incident momenta, typically above 3 GeV/c. Statistics has been severely limited in these measurements for the region below $m_{\pi\pi} \approx$ 500 MeV. Several authors [8] have recently suggested the region below 400 MeV incident pion energy as particularly suitable for a model-independent determination of threshold $\pi\pi$ scattering parameters relying on the Chew-Low method. In this respect LAMPF offers a unique combination of resources, not found in any other accelerator laboratory in the world, i.e., an intense pion beam at energies between 300 and 500 MeV, and the Neutral Meson Spectrometer (NMS), a large-acceptance high-resolution device for detection of π^0's.

Using the NMS in the P^3 beam line, with incident pion kinetic energy 350 MeV, we propose [9] to measure exclusive cross sections for the reaction $\pi^+ p \rightarrow \pi^+\pi^0 p$, focusing on the low $m_{\pi\pi}$ portion of the phase space. Other equipment required for this measurement includes a liquid hydrogen target inside a large evacuated thin-walled scattering chamber, and an array of charged particle detectors with particle identification capable of resolving pions and protons with good energy resolution. The charged particle detector array will be designed to achieve high acceptance for coincident events characterized by low values of the four-momentum transfer to the nucleon, as required for the Chew-Low analysis. Assuming realistic parameters for the apparatus in question, the required event statistics can be achieved in a run of reasonable length.

In summary, a precise knowledge of the $\pi\pi$ interaction at low energy is essential both to testing QCD and to providing a data base for evaluation of pionic interactions in more complex processes. Acquiring this knowledge will need a synthesis of efforts on both experimental and theoretical fronts.

III. DIBARYON SEARCHES

Almost any QCD-inspired model predicts the existence of six-quark structures that are loosely referred to here as dibaryons. The energy spectrum of the dibaryons is somewhat model-dependent, and the predictions must be checked experimentally whenever possible.

Searches for dibaryons have been carried out in the nucleon-nucleon interaction, and some researchers find evidence for them in this process. For various reasons, one expects pion reactions on nuclei to be favorable for the formation of dibaryons if they exist. For one thing, nuclei consist of multiple numbers of nucleons (and hence quarks) in close proximity; secondly, pions can be thought of as a source of energy and momentum that can be "dialed" to create kinematic conditions favorable to creating a dibaryon when the pion is absorbed by the quarks.

Several dibaryon candidates likely to be seen in pion reactions have been suggested. Based on a QCD string model, a dibaryon d' with I, even $J^P = 0^-$, and mass about 2.06 GeV has been predicted. Due to its quantum numbers, it cannot decay into NN, but only into $NN\pi$ channels. It could thus be formed in pion double charge exchange (DCX) near $T_\pi \approx 50$ MeV. This dibaryon resonance could manifest itself in DCX reactions on any nucleus and in any transition, depending only on the probability of $NN \to 6q$ in a particular nucleus. It has been proposed that it might be responsible for a peculiar and universal energy dependence of observed DCX cross sections (the forward-angle cross section peaking at about 50 MeV). Calculations [10,11] for particular nuclei support the d' idea, although a competing explanation [12] suggests that at least part of the observed energy dependence is due to the sequential single charge exchange process. Having independent measurements to support the dibaryon interpretation would be highly desirable.

A second dibaryon [13], the d^*, appears in all realistic models. This is a spin-3, isospin-0 dibaryon, which may be thought of as a bound state of two $\Delta(1232)$'s. It is referred to as a d^* to reflect the fact that its quantum numbers are those of a spin excitation of the deuteron. The d^* is found to be deeply bound with respect to two $\Delta(1232)$'s because its quarks are rather spread out compared to those in the $\Delta(1232)$. This lowers both the (repulsive) color-magnetic energy as well as the kinetic energy of the quarks in the region of confinement. Calculations put the d^* in the region of 2.1–2.3 GeV, where the state is quite narrow due to limited phase space for decay into states containing pions, and due to a poor overlap of its wave function with that for two nucleons only.

1. Inclusive Pion Spectra and Coincidence Measurement in $\pi^- + ^3\text{He} \to \pi^+ + 3n$

In the particular case of the DCX reaction on ^{3,4}He isotopes, there is no bound system in the final state. For these nuclei, the conventional calculations do not reproduce the reaction observables that have been measured. A recent calculation [14] of the DCX cross section predicts significant enhancement in the excitation function close to the threshold for d' production (~60 MeV for ^{3}He). At the same time, a comparison of the conventional calculations with experimental data demonstrates that they underestimate the data at low energies by more than an order of magnitude, whereas at energies above 140 MeV, agreement is quite good.

A measurement of inclusive pion spectra and coincidences with the neutrons from the reaction $\pi^- + ^3\text{He} \to \pi^+ + 3n$ for T_π from low energies through the resonance at a forward pion angle has been proposed (LAMPF experiment 1322) to search for the d'. The experiment would entail the measurement of the energy dependence of the doubly differential cross section $d^2\sigma/(d\Omega dT_\pi)$. If the d' hypothesis is correct, the resonance will be seen in an invariant mass spectrum of the $(\pi^+ nn)$ system and in the missing-mass spectrum with respect to a neutron. At the same time, at energies just above the threshold, there will be a peak in the spectator neutron energy because of the quasi two-body final state. The data will also make it possible to verify prediction of a significant enhancement in the excitation function near the threshold of predicted d' resonance production (~60 MeV). The measurements could be done using the CLAMSHELL spectrometer with three arrays of neutron detectors and a liquid ^{3}He target in the Low Energy Pion (LEP) channel, which provides uniquely appropriate conditions for this experiment.

Additionally, the experimental data to be obtained will extend our understanding of the DCX reaction mechanism and allow us to (1) study the energy spectrum to verify whether the unusual structure indicated by some measurements in this energy range actually exists; (2) compare characteristics of DCX on ^{3}He with the existing data on ^{4}He; and (3) provide additional information for understanding the mechanism of the DCX reaction from observation of neutron energy spectra in coincidence with the pion.

These data may also reveal the existence of the d^* in the mass region between 2100 and 2300 MeV/c^2 [13], as discussed further below.

2. A Search for the d^*

The total cross section for production of this object in the reaction $\pi + d \rightarrow \pi + d^*$ is estimated to be of the order of 0.5 microbarn. Such a small cross section would not yield a convincing signal above backgrounds. Therefore it has been suggested that, since the large extension of the deuteron wave function is partly responsible for the diminished cross section, a more compact target may lead to a significantly increased cross section, by as much as a factor of 10. Furthermore, the feature of the DCX reaction that one detects a pion having the opposite charge from that of the beam reduces the severity of the background.

With these assumptions, a possible search scheme would be to measure the missing mass in the process ^{3}He$(\pi^-, \pi^+ n)$X with respect to the detected neutron. The π^+ is presumed to be a decay product of the d^* along with the undetected particles in X. The signal-to-background estimates for such detection are better than 1:10, given that the neutron detection can be done at very small angles ($\leq 10^\circ$). If sufficient running time (~120 hours at each of several energies) were made available, we would be able to demonstrate the existence of this dibaryon to better than 5 standard deviations in the mass region between 2000 and 2250 MeV, given the expected cross section. If the cross section is smaller, then one will have established an upper limit of ~1 microbarn at the 99% confidence limit should there be no indication of a signal 2.7 standard deviations above the background.

The existence or nonexistence of the d^* well below Δ-Δ threshold is a significant test of our basic understanding of QCD in the multiquark sector. If it is ruled out in this region, it would imply that *only* molecular-type composites of hadrons may be formed, and thus would require significant revisions to the construction of non-lattice models of QCD.

IV. Δ'S AND π'S IN NUCLEI

The pion is strongly coupled to baryon resonances. At LAMPF energies, the favorable situation prevails in which the pion is capable of exciting a prominent resonance, the Δ(1232). The Δ(1232) appears as an isolated resonance, and it dominates the pion-nucleon scattering amplitude at energies between 100 and 300 MeV. For this reason, pion beams have allowed one to study in some detail the behavior of this resonance in the nuclear medium, where its interaction with other nucleons can be observed.

In conjunction with electromagnetic probes, phenomenological determinations of the mass and width of a real Δ(1232) in the nucleus have been made. The capability to produce the Δ(1232) resonance with pions in charge exchange reactions, as well as in elastic and inelastic scattering processes, provide many possibilities for studying its interactions with nucleons. In fact, many more possibilities exist with pions than have actually been exploited.

Such experimental studies of the Δ(1232) in nuclei are more important now in nuclear physics than foreseen a decade ago when much of the initial work began. This is because properties of elementary hadrons (nucleons, Δ(1232), pions, hyperons, etc.) are being increasingly recognised as "fundamental" in the sense that they are directly related through methods of QCD sum rules [15–17] to a relatively small set of quark and gluon condensates. It now appears that the same methods apply to hadrons in nuclei [18–20]. However, in nuclei the condensates develop a density dependence, and the four-quark condensates appear to play a more important role than they do in free space. At the present time, the four-quark condensates are very poorly known, and medium-energy physics has an opportunity to make important contributions to their empirical determination. For example, knowledge of the mass shift of the Δ(1232) in the nucleus has been used to determine a specific linear combination of four-quark condensates [21]. Other properties of deltas in nuclei, for example the spin dependence of the delta-nucleus interaction, determine other linear combinations. Experiments aimed at determining properties of the Δ(1232) in nuclei, including possibilities not yet explored, assume a new importance in this context, providing basic values for the presently unknown condensates in nuclei. Identifying the relevant experiments is of general importance in the area of nonperturbative QCD because these same condensates determine how any hadron behaves in nuclear matter, a problem related to early-universe phase transitions.

1. Δ(1232) Dynamics and Medium Modifications

To date, most of the reactions that have been brought to bear on the medium-modification of the Δ(1232) are exclusive reactions. Such reactions take advantage of known properties of nuclear states as filters for different spin/isospin components to determine the interaction of the Δ(1232) with the nucleus. For example, pion double charge exchange to nonanalog states has been used to quantify the isovector spin-spin and tensor interactions of the delta with nucleons. Measurements on light nuclei and those taking advantage of polarized-target technology can be designed to explore as yet undetermined aspects of the delta-nucleon interaction, for example its isoscalar spin-spin components (see Sect. V, below). These are directly related to determining four-quark condensates as described above.

Reactions to the continuum in nuclei are yet another means to quantify the Δ(1232)-nucleus interaction. The intense beams and large-acceptance detectors available at LAMPF will allow observation of a nucleon in coincidence with the outgoing pion in regions of phase space sensitive to the $\Delta(1232)$-nucleus interaction (see also Sect. VI, below). Such measurements also have the possibility of being extended to higher energy where properties of more massive baryon resonances in nuclei become available for study and where energy resolution needed for exclusive measurements becomes problematic. The masses of these resonances and their coupling to pions provide yet additional constraints on the quark-gluon condensates in nuclei.

2. Non-Nucleon Constituents in Nuclei

The degrees of freedom that are observed at low momentum transfer in free space are the meson and baryon degrees of freedom. One has long expected that the same set of hadrons should be found as constituents of the nucleus, i.e., that the traditional picture of the nucleus as simply a collection of nucleons is incorrect in detail. Although models predict a definite role for pions and the $\Delta(1232)$ (for example) in the nuclear wave function, it has proved to be very difficult to find any empirical evidence for the existence of these constituents.

Recently, however, it has been shown that the reaction $(\pi^+,\pi^- p)$, under favorable kinematic conditions, provides a promising, general means of studying non-nucleonic degrees of freedom in nuclear matter. Exclusive measurements of the $(\pi^+,\pi^- p)$ coincidence double-charge exchange (DCX) reaction have been performed with 500-MeV pion beams. For events with small (<50 MeV) missing energy (to suppress sequential scattering), there is a broad peak in the π^- spectrum near the position of the quasi-elastic peak that is seen with similar cuts in the π^+ spectrum from $(\pi^+,\pi^+ p)$ coincidence measurements. The π^- peak is what one would expect of a one-step (quasi-elastic) DCX reaction taking place on a Δ^- component of the nuclear ground state. Based on this picture, the probability with which the negatively charged $\Delta(1232)$ is found in the nucleus has been determined.

Similar pion-induced exclusive reactions can be used to study the different Δ charge states in the nucleus. This method is applicable across the periodic table. These reactions can also be exploited as a systematic method of studying other non-nucleonic degree of freedom in nuclei. For example, one can look for pionic components in the nuclear wave function by observing two pions from the $^{12}C(\pi^+,\pi^-\pi^+)$ reaction at the kinematic limit, which corresponds to the production of the ^{12}N nucleus in or near its ground state. At higher pion energies, one would have the possibility of learning about heavier mesons and baryon resonances in nuclear ground states.

V. π REACTIONS ON POLARIZED NUCLEAR TARGETS

Experiments with pions on polarized protons and polarized light and heavy nuclear targets can provide fundamental information about the structure of elementary hadrons, the $\Delta(1232)$-nucleon interaction, and about the shape of the neutron density distribution in nuclei. Several experiments with polarized proton targets were discussed in the section on pion-nucleon scattering. In recent years, several pioneering and high-quality experiments with pion reactions on polarized nuclear targets have been carried out. As one might anticipate, the results typically do not conform to prior expectations. One example is π^+ elastic scattering from ^{15}N: whereas large analyzing powers with strong oscillatory structure were predicted by various reaction models, the data were found to be close to zero throughout the angular range. A full understanding of this issue is still not in hand, but as our examples suggest, this discrepancy could indicate important sensitivity of this type of measurement to the spin-dependent Δ-nucleon interaction.

1. Pion Elastic and Charge-Exchange Scattering from Polarized ^{3}He

Asymmetries from pion elastic scattering on polarized nuclei are sensitive to the details of the pion-nucleus reaction mechanism, and to the nuclear spin density. Because theoretical analyses of asymmetry data from pion scattering on spin-1/2 nuclei in the $1p$-shell have failed to reproduce the data, attention has turned to π^+ elastic scattering from polarized ^{3}He (LAMPF Experiment 1267), which may hold the key to an understanding of the pion-nucleus reaction mechanism.

Of particular interest is the evidence for a signature of the Δ-neutron spin-spin interaction in the asymmetry. Relatively large negative A_y were observed in at incident energies near the centroid of the resonance at forward angles. There, standard theoretical calculations using a first-order optical potential and state-of-the-art Faddeev wave functions predict small positive A_y. A preliminary calculation by Jennings that includes the Δ^{++}-neutron spin-spin interaction, derived from a meson-exchange model, gives an excellent fit to the asymmetry data at 180 MeV, but does not yet reproduce the energy dependence of A_y. This work should provide a quantitative estimate of the magnitude of the Δ-nucleon spin-spin interaction, which is of great interest to current quark models of the baryon-baryon interaction.

Additional data are needed to test the Δ-nucleon interaction model. For example, the asymmetry for π^- scattering on ^{3}He is predicted to be quite insensitive to this interaction. Therefore we have proposed a π^- scattering experiment as a critical test of the model (LAMPF Experiment 1317).

The first data on the single-charge exchange (SCX) reaction (π^-,π^0) on polarized ^{3}He (LAMPF Experiment 1300) have been taken at one incident energy, employing the NMS and the TRIUMF high-pressure gaseous target that has reached a polarization of 70%. The SCX reaction measures the isovector part of the reaction amplitude and is thus a necessary complement to the elastic scattering data. Calculations for the analyzing power in the SCX reaction including the Δ-nucleon spin-spin interaction are under way.

At higher incident energies ($T_\pi \geq 300$ MeV), the asymmetry becomes increasingly sensitive to the small components in the ground-state wave function of ^{3}He (components other than the fully symmetric S state). Information on the small components is needed in the context of the measurements of the spin structure function of the neutron using a polarized ^{3}He target. Measurements at energies above 300 MeV can be done with the high beam currents available only at LAMPF.

It important to keep in mind an important difference between pion scattering and electron scattering. In the case of electron scattering on few-nucleon systems, interactions of electrons with exchanged mesons, π's, ρ's, etc., play a major role, making the extraction of high-momentum components of the charge density from large q data model-dependent. For pion scattering, it is known that this type of exchange current plays a relatively small role, and thus asymmetry data obtained with pions at any energy are of interest.

2. Excitation Function of the ^{13}C(π^+,π^0) Reaction across the Δ(1232) Resonance

Once the analysis of the elastic and SCX asymmetry data from ^{3}He has led to an understanding of the pion-nucleus reaction mechanism, it will be possible to extract the information on the nuclear spin density, which is contained in the asymmetry data for the 1p-shell nuclei. Since the isoscalar part of the pion-nucleon scattering amplitude is larger than the isovector part by a factor of two at Δ-resonance energies, pion scattering provides information on the isoscalar part of the spin density, which cannot be obtained easily from back-angle elastic electron scattering (which is dominated by the isovector part).

Significantly better quality data than are currently available for elastic pion scattering from polarized ^{13}C and ^{15}N are needed at several incident energies in addition to high-resolution SCX data on the same nuclei using the NMS. This work will provide data for tests of the spin densities predicted by recent large shell model calculations. It will also lead to an understanding of the medium modifications of the spin-dependent parts of the pion-nucleus interaction, such as by the spin-dependent Δ-nucleus interaction.

With these data, a long-standing puzzle may be resolved: whereas the excitation function of π^+ inelastic scattering to the 1^+, $T = 0$ state of ^{12}C (12.71 MeV) follows DWBA predictions, that for the 1^+, $T = 1$ state (15.11 MeV) strongly differs. The DWBA predictions are nearly the same for the two states, but the isovector transition follows the excitation function for free (!) π-N scattering, suggesting that the nucleus is not even present. This bizarre situation is not understood. Does it occur elsewhere? The IAS transition for the ^{13}C SCX reaction contains the same isovector spin-dependent amplitude as for the 15.11-MeV case. It interferes with a spin-independent amplitude, giving rise to an analyzing power, whose angular distribution has been measured at one energy. The energy dependence must also be explored in order to help resolve the known problems in the theoretical description of spin-dependent effects in pion-nucleus interactions.

3. Pion SCX on Oriented ^{165}Ho and Similar Targets with the NMS

In a previous experiment, the deformation of the neutron density distribution of ^{165}Ho was found to be smaller (about 84%) than the deformation of protons, an observation that has stimulated models of F-spin symmetry breaking in the interacting boson model. The relative size of the neutron deformation can be quantified more precisely with the NMS. This instrument will provide a higher-resolution spectrum and permit a more accurate analysis of the orientation asymmetry, which is sensitive to the deformation ratio. Experiments are also possible on other nuclei, including oblate nuclei and nuclei in the actinide region.

VI. π-FEW NUCLEON REACTIONS

The few-nucleon system is desirable for studies of hadron dynamics because the multiple scattering of the pion before and after the reaction of interest is minimized, and thus the signature of the reaction of interest is clearer than in a larger nucleus. Furthermore, nuclear structure issues in light systems are in principle under control, since they are amenable to study using exact Faddeev methods, which have been vigorously pursued in the few-body physics community. Below, we describe briefly some experiments that take advantage of these points.

The principal issues range from specific questions about reaction dynamics to measuring properties of baryon resonances in a nuclear medium. In the former category, we would mention characterizing how the fundamental πN interaction takes place in the presence of other nucleons (the "in-medium t-matrix"). This can be mapped out in some detail; for example, one can isolate the isoscalar and isovector amplitudes by looking at scattering without and with charge exchange. Other issues that can be addressed by carefully designed experiments include: the extent of competition between scattering and absorption (absorption cannot happen on a single free nucleon), the probability of double and higher-order scattering processes, NN correlations, the coherent involvement of more than two nucleons in absorption, the role of the Δ and other isobars in these reactions, and the probability of pre-existing Δ components in nuclear ground states. Experiments dealing with many of these issues have been approved by the LAMPF Program Advisory Committee.

1. Single Charge Exchange in the Mass-3 System

Several theoretical calculations of single charge exchange in the mass-3 system [^{3}He$(\pi^-,\pi^0)^3$H and ^{3}H$(\pi^+,\pi^0)^3$He] indicate that the modification of the elementary $N(\pi^\pm,\pi^0)$ amplitude is profound, even with as few as two additional nucleons. The magnitude and energy-dependence of the angle-integrated cross section for SCX in the mass-3 system in the Δ-resonance region are very different from those for the free nucleon. There are no data that allow this angle-integrated cross section to be deduced. These measurements provide an opportunity for effective utilization of the capabilities of the neutral meson spectrometer (NMS) at LAMPF.

2. Double Charge Exchange in ^{3}H, ^{3}He, and ^{4}He

Double charge exchange in ^{3}H, ^{3}He, and ^{4}He can be used as a tool to investigate pion double scattering in the simplest nuclear systems, since two like-charge nucleons must be involved in order for DCX to occur. The available inclusive data [(π^+,π^-) or (π^-,π^+)] in the Δ-resonance region are consistent with the dominant mechanism being sequential single charge exchange, although theoretical calculations so far have achieved only qualitative agreement with the measured cross sections, suggesting the existence of more exotic and more interesting mechanisms such as those involving the creation and interaction of isobars.

To confirm the existence of specific nonsequential mechanisms, one must do more difficult, more kinematically complete experiments. The intense beams and large-acceptance detectors available at LAMPF will allow detailed exploration of DCX with the observation of one or more nucleons in coincidence with the outgoing pion. One can choose the kinematics to observe regions of phase space that are expected to be populated by particular reaction mechanisms. In the case of several competing mechanisms, one can use features such as energy dependence of cross sections to distinguish among them.

3. Delta-Nucleon Interactions in ^{3}He($\pi^\pm$, $\pi^\pm$, n)pp

Since the neutron in ^{3}He carries most of the spin of this nucleus, one might expect quasi-free pion scattering on polarized ^{3}He to offer the possibility of determining pion scattering cross sections from a polarized neutron target (averaged over the momentum spread of the neutron in ^{3}He). This would be true assuming the absence of initial and final state interactions, and, in the Δ(1232) region, assuming the absence of an interaction of the Δ(1232) with the remaining spectator pp pair. Given the expectation that initial- and final-state interactions are small for light nuclei, the asymmetry for quasi-free neutron knockout from polarized ^{3}He should thus be a direct and sensitive measure of the spin-dependence of the Δ-proton interaction. Future measurements of the polarization of a final proton or deuteron can be envisioned. These would give further information on the interaction of the Δ(1232) with neutrons and protons.

4. Study of Three-Nucleon Systems using π^- Capture on ^{3}H and ^{3}He

Experiments using stopped pions in the three-nucleon system (LAMPF Experiment 1286) make it possible to learn whether the long-standing discrepancy between scattering lengths inferred from data on multibody final state reactions (such as the $d(p, 2n)p$ reaction) and the $d(\pi^-, 2n)\gamma$ reaction arises from multibody complications in the former (such as the elusive three-body force), or from uncertainties in the description of the pion entrance channel. The proposed study will be carried out through measurements of coincident γ-ray spectra from both the ^{3}H(π^-, $3n$)γ and the ^{3}He(π^-, p, $2n$)γ reactions in a kinematic regime where at least two of the outgoing hadrons have relatively little (1–10 MeV) kinetic energy.

A further aim of the experiment is to explore few-body physics in the exotic three-neutron system generally. Data obtained here will provide a test of the pure $T = 3/2$ three-nucleon state without contamination by a strongly interacting spectator particle (a limitation of previous measurements).

VII. SINGLE AND DOUBLE CHARGE EXCHANGE

The single and double charge exchange reactions provide unique windows on hadron dynamics and nuclear structure. The double charge exchange reaction is interesting because the pion is guaranteed to have interacted with at least two nucleons in the reaction. Using the DCX reaction, an entirely new area of nuclear structure has been opened up with the discovery and systematic study of double giant resonances in nuclei. Additionally, DCX has been successfully used for creating new neutron- and proton-rich nuclei, for quantifying the isovector spin-spin and tensor interaction between the $\Delta(1232)$ and a nucleon, and for providing a striking confirmation of seniority correlations in shell-model wave functions.

The LAMPF accelerator, by virtue of its intensity and array of multi-purpose spectrometers, is the best facility in the world for measuring single and double charge exchange. This includes the recently completed neutral meson spectrometer (NMS), which, among other things (detailed in other sections of this document), is expected to play a crucial role in establishing the limits of validity of the sequential mechanism of double charge exchange, the mechanism that has been expected to dominate the pion DCX reaction throughout the energy region accessible at LAMPF.

1. Studies of Exotic Nuclei

Exotic nuclei, i.e., nuclei having unusually large neutron and proton excesses, are of general interest in many branches of nuclear science and are difficult to study because they exist far from stability. These nuclei may be produced, and their masses determined, with pions by exploiting several different reactions, including pion absorption and pion double charge exchange.

Exotic nuclei are characterized by very weak binding of the last neutron (or proton) pair, implying that the excess nucleons extend well beyond the core. Pion DCX provides a means to study the dynamics of these nuclei. A direct measure of the size of the neutron halo is given by DCX cross sections, since the cross section scales as the root-mean-square radius of these neutrons to the -6^{th} power. Additionally, soft dipole modes may appear, and DCX provides a source of experimental information about these interesting states. Exotic neutron-rich nuclei that can be studied in the (π^-, π^+) reaction include ^{10}He, ^{11}Li, ^{14}Be, and ^{17}B. Exotic proton-rich nuclei that can be studied in the (π^+, π^-) reaction include ^{9}C, ^{10}C, and ^{11}N.

Several very interesting cases can be studied in double charge exchange on ^{10}Be. M. Gornov and P. Morokhov from the Moscow Engineering Physics Institute have pointed out that it is possible to make ^{10}Be using the LAMPF proton beam with the reaction ^{11}B$(p, 2p)^{10}$Be. The cross section is approximately 25 mb. A target of this material can be produced with a 1-inch target of isotopically pure ^{11}Be with a density of 2 gm/cm^2 installed in the isotope production region at LAMPF and irradiated with 800 μA of protons at 85% beam on for three months. The ^{10}Be can be chemically separated from the boron at the end of the irradiation.

The nucleus ^{10}Be is the lightest $T = 1$ target. This target provides as close to a pure di-neutron to di-proton transition as one can get for studying the DCX mechanism. In the ^{10}Be$(\pi^+, \pi^-)^{10}$C reaction, it should provide the largest DCX double analog state cross section, in excess of 10 μb/sr (at 0°) in the resonance region and above. With the LEP channel and "software scrunching," one will be able to put 2×10^9 pions/sec through a 4-cm^2 (1-mg/cm^2 thick) target. With this target cross section and beam, and with the LAS spectrometer, one can obtain 65 cts/hr in the double isobaric analog state DCX transition.

Another interesting DCX reaction is ^{10}Be(π^-,π^+)^{10}He. Currently there is no published observation of the doubly magic ^{10}He ground state, although there are rumors that it has been observed. Based on systematics, the cross section for this reaction is expected to be on the order of 1 μb/sr. With a flux of 4×10^8 pions/sec, one could obtain 1 count/hr in the ^{10}He ground state. Measuring this cross section would allow the neutron radius in ^{10}He to be accurately determined using the same technique that has been applied in other neutron-rich nuclei [22].

Stopped pion absorption in light, neutron-rich targets and subsequent detection of one charged particle, or two charged particles in coincidence to study the residual nuclei constitutes a second technique to create and study exotic nuclei. With good-resolution solid state detector telescopes, which permit the identification of p, d, t, ^{3}He, and ^{4}He, up to twenty different final-state nuclei can be investigated in one experiment. For example, with a ^{14}C target, helium isotopes through ^{10}He can be studied. This technique was pioneered in Russia and has only very recently been used at LAMPF.

2. Confirming the Theory of DCX

Recent theoretical developments have been leading toward a comprehensive microscopic theory of double charge exchange to discrete states. The theory describes quite well the SCX and DCX data from the lowest energies up to 300 MeV. At low energies, the data appear to be explained almost entirely as sequential single charge exchange, although residual discrepancies have been noted and could possibly signify a small but significant role for more exotic processes. Such processes include effects such as short-range pair correlations between nucleons, which have long been conjectured to play an important role in low-energy DCX. In order to make the quantitative study of these correlations possible, it is necessary to provide the strongest possible experimental constraints on the sequential contributions of double charge exchange. Until recently, the data necessary for this study have not been available.

The experiments that can provide a direct test of the sequential theory [12] require the neutral meson spectrometer (NMS), and consist of measurements of single charge exchange to the excited intermediate states in the sequential process. If discrepancies between the measurements and predictions of SCX cross sections are noted, the new data would provide experimental input needed to complete the model of the sequential process. The cross sections of this type needed to check the theory have not been possible previously because of the lack of the required energy resolution for detecting neutral mesons. It would be desirable to have such measurements at a variety of energies, since the pion-nucleon scattering amplitude changes character (strength and relative sizes of various spin/isospin components) as the energy is varied from low energies, where the nucleus is transparent, to resonance energy, where the nucleus is quite black. Measurements on a few nuclei of different isospin are also needed, since the interplay between nuclear structure and multiple scattering is quite different for zero and non-zero isospin cases.

3. An Improved-Yield (30–1000×) Spectrometer System for DCX at LAMPF

Up to now, the EPiCS channel and spectrometer has been the system of choice for DCX experiments at LAMPF. This system is optimized for experiments with a few hundred keV resolution and energies from 150 MeV to 300 MeV. The large beam spot required by the EPiCS energy-loss system also reduces the available counting rate when small separated-isotope targets are required. DCX experiments, however, deal with very low cross sections (a fraction of a microbarn per steradian) and rare separated isotope targets, and could accept 1-MeV resolution if a larger counting rate and smaller beam spot could be obtained. The Low Energy Pion Channel (LEP) has a larger solid angle and momentum acceptance than EPiCS, but suffers from the problem that monochromatizing slits must be used in order to get sufficient resolution, thus reducing the counting rate below that of EPiCS.

A new technique [23] has been proposed to improve the energy resolution of LEP, namely the use of time-of-flight (with reference to the 201.25-MHz rf structure of the LAMPF proton beam) to measure the energy of the incoming pions, allowing use of the full LEP pion beam without closing the slits. Time will be measured in a set of time-of-flight counters in the focal plane of the LAS spectrometer, which will be moved to LEP for these experiments.

Some beam development time was used for an experiment to measure the time spread of the pion beam at LEP. In this experiment, performed in November 1994, the front-end quadrupoles of LEP were not operational. A small phase-space beam was used to measure the intrinsic time resolution of the technique of comparing the pion arrival time with the 201.25-MHz rf. This resolution was measured to be 120-ps FWHM. Improvements in the technique are possible, with better resolution expected in the future. The 120-ps resolution already demonstrated, combined with the expected resolution of the LAS spectrometer (0.6 MeV with vacuum coupling in the dipole region) and a 2-gm/cm^2 target, gives the overall energy resolution and yield improvement factors shown in Table I. Note that the spot size of LEP is approximately 5 cm $\times$ 1 cm, compared with 10 cm $\times$ 20 cm for EPiCS. This results in an additional yield gain of $\times$40 for experiments in which a limited amount of target material is available.

TABLE I. Energy resolution and yield gain factor for DCX at LEP

Energy (MeV)	30	50	100	140	180	250	300
Resolution (MeV FWHM)	0.9	0.9	1.0	1.2	1.4	2.0	2.4
Yield (LEP/EPiCS)	43	46	35	32	30	28	27
Small-Target Gain	1610	1840	1400	1280	1200	1120	1080

VIII. π DYNAMICS AT HIGHER ENERGY

The mechanism by which pions transport energy and momentum as they propagate in nuclei has been the object of extensive experimental and theoretical studies in the region below about 300 MeV in pion kinetic energy. Models have been constructed in this energy region that compare favorably to integrated (partial) reaction cross sections. One generally concludes from these results that the reactions are occurring in the surface (lower density regions) of the nucleus and that the theory is well under control here.

It is a fundamental issue of many-body theory to extend the existing, successful theories of pion transport to higher nuclear density. It also is a subject of practical import, both at energies where existing theories are rather well tested (below pion energy 300 MeV) and at higher energies. Pion energies between 300 and 600 MeV, accessible at LAMPF, constitute a region where the data necessary to build such a theory are rather incomplete. New physics is encountered, the physics of pion production. The pion production channel in the pion-nucleus interaction is starting to become important at pion kinetic energies above 400 MeV. The consequence of this channel opening is not very well understood in pion transport models, and it is very important to come to such an understanding.

Studies at current LAMPF beam energies and higher have practical importance, as successful transport theories will eventually be needed in wide-ranging experimental investigations at high-energy accelerators for the purpose of modeling the final state in various studies of hadron dynamics in nuclei. For example, modeling transport pions originating from baryon resonance decay in nuclei can be expected to be necessary for interpreting data collected in the CEBAF nucleon resonance program. The relationship between pion reactions and heavy-ion reactions is also close because energetic heavy-ion reactions generate pions by nucleon-nucleon collisions, and the propagation of these pions is an important means of energy transport for these reactions.

Already, there is some indication of difficulties with standard transport descriptions even in the $\Delta(1232)$ resonance region. A comparison of cross sections for deeply inelastic pion scattering (see A., below) with spectra generated with standard Intranuclear Cascade (INC) models, including the code RQMD, indicates large discrepancies that could have caused difficulties for modeling of heavy-ion experiments. The code RQMD is expected to be used for predicting features of high-energy heavy-ion reactions that may lead to evidence for the quark-gluon plasma.

A. Pion Dynamics at Higher Density

It has been discovered recently in all models tested that theory is very much in disagreement with measurements of deeply inelastic pion reactions. In particular, (π, π') spectra obtained in the scattering of 500-MeV pions from carbon are seen to have a spectral shape in which the quasi-elastic peak and the large energy loss portion of the spectra are well reproduced by INC calculations. However, the region of the spectra corresponding to pion energies that strongly excite the $\Delta(1232)$ is predicted to be a factor of 5 to 10 smaller than the data. This could be related to the fact that we do not yet understand how pions behave when they penetrate farther inside the nucleus, and it also establishes the relevance of deeply inelastic pion scattering as an experimental probe of higher density physics.

B. Opportunities with Higher Energy Pion Beams

An important direction for extending these studies is toward a theory of transport for higher energy pions (above 300-MeV kinetic energy). Higher energy is interesting for several reasons. One is that the pion is naturally more penetrating, and so high density is reached already in elastic reactions. Another (perhaps related) is that the models that work well below 300 MeV seem to deviate systematically from (the paucity of) data that exist at the higher energies. Such simple observables as elastic scattering, total cross sections, and total reaction cross sections seem to be underestimated by theories extended into this energy region [24]. However, because many of the experiments are very old, one needs reliable measurements of the elementary reactions for a few cases to confirm that the disagreements are not the result of inaccurate data.

1. Total Cross Sections

In order to build a theory of pion transport in any energy region, the basic experimental quantities are elementary cross sections (elastic and total) and partial reaction cross sections, consisting of pion production, absorption, and quasi-elastic scattering cross sections. The LAMPF beam extends up to about 600 MeV, and the studies of pion transport can be extended to these energies with appropriate data sets. The energy range can be extended to somewhat higher energies with use of superconducting cavities (see next section).

Total cross sections as well as total reaction cross sections are important and basic observables for any scattering system, but the experimental situation is very thin for pions on complex nuclei at energies beyond the $\Delta(1232)$ resonance region. Only a few points for nuclei no heavier than carbon are known. Beyond the Δ the many other nucleon resonances seen in free scattering are observed to melt together in recent photonuclear total cross-section data on a wide range of target masses. The same seems to be true for the sparse pion data. A solid energy dependence for several nuclear targets with both pions and photons will strongly constrain models of alterations of baryons within nuclei. Pion total and reaction cross sections will also provide an independent observable for reaction models for pions on nuclei at higher energies, and extending measurements to 575 MeV (LAMPF Experiment 1279) will nearly double the coverage now available for any but the lightest nuclei.

2. Quasi-Free Pion Scattering

The $(\pi, \pi' p)$ reaction in quasi-free kinematics provides an extremely clean signal of the scattering of pions from protons and determines an important contribution to the total reaction cross section for pions on nuclei. There is no reason to believe that the pion-nucleon cross section is the same in the nucleus as it is in free space, as the pion coupling to baryons is changed in the medium through the influence of four-quark condensates. The ratio of the quasi-free $(\pi^+, \pi^{+\prime} p)$ and $(\pi^-, \pi^{-\prime} p)$ cross sections affords a means to study the modification of the πN interaction in the nuclear medium. Large deviations of the $(\pi^+, \pi^{+\prime} p)$ to $(\pi^-, \pi^{-\prime} p)$ ratio relative to the free ratio have been observed in nuclear targets at beam energies near the $\Delta(1232)$ resonance.

Similarities of pion scattering data with (e,e') data for the same three-momentum transfer [25] suggest a complementary role for pions and electrons in exploring this physics. It would be of interest to increase the pion energy and see whether the region in which the data are enhanced over the prediction continues to lie between the quasi-elastic peak and the region that in electron scattering corresponds to the excitation of a nucleon to the $\Delta(1232)$.

3. Pion Production and Absorption Cross Sections

The role of pion absorption in pion transport is relatively well understood, since this channel is open even at threshold. The situation is different for pion production, since it opens only at about 450 MeV, where relatively few experiments have been carried out. Actually, very few studies of either pion production or pion absorption on nuclei exist in this energy range, and experiments on a variety of nuclear targets under different kinematic conditions should be undertaken.

4. High Nuclear Excitations from Pion Reactions

The most direct means of studying the transport of pions through nuclei is to observe the outgoing pions. This certainly neglects pion absorption, probably the most interesting process of all. Absorption, and any other very lossy mechanisms, will give rise to a very highly excited nucleus. We can observe the processes by which this nucleus de-excites to infer its properties, guided by the vast experience with heavy-ion reactions. This gives a new and independent look at how the pion beam interacted with the target nucleus, to complement measurements of the outgoing pions. It is the excitation energy, or in some limit the temperature of the nuclear reaction products, that we address here.

Nuclear temperatures can be inferred from several types of data, as recently surveyed [26]. Slopes of the energy spectra of emerging nucleons are distorted by the direct absorption process that yields some very high-energy products. Light nuclei such as deuterons are also too common at high energies because of the final-state interactions of the many nucleons. Fission is a good probe of thermal equilibrium very late in the history of the de-excitation. The temperature may have cooled by the time fission gets around to happening, so some lower estimate is provided by the fission probabilities of medium-heavy nuclei. High fission probabilities are present when the excitation is large, compared even to the large barriers for fission of medium-heavy nuclei. We have a solid set of measurements on fission probabilities induced by pions, so this process is known. One conclusion is that the excitation of a nucleus that fissions saturates at about 200 MeV. Fission is thus not suited to examine higher excitations.

There are at least two measures of temperature possible from observations of intermediate mass fragments (IMF), those with Z from about 4 to 14. The slopes of their energy spectra give a temperature parameter less contaminated by direct processes than those of simpler ejecta. The mass spectra themselves are specific to the temperature of the emitting source due to the wide range of separation energies examined, with each being found in an exponent with the temperature.

By these clues from heavy-ion reactions we are led to propose to measure the mass and energy spectra of IMF from pion reactions on heavy nuclei. Even single-arm detectors could provide the basic spectra. Cross sections will not be large, targets must be thin, and the pion beam will never be intense. We expect, therefore, to require a detector of large solid angular acceptance about the target. A number of these have been developed for heavy-ion studies, and their designs can be adapted to our needs. A first simple experiment to count IMF with very poor resolution is now being analysed, using pions from the AGS. The results of this study will help us design the best counter experiment for the next phase at LAMPF.

A detector with a large solid angle can also count the multiplicity of IMF produced in a pion reaction. The probabilities of each order of multiplicity are known from heavy-ion reactions to be another measure of the nuclear excitation energy. Our experiment should thus give several independent ways to infer this quantity.

A very few heavy nuclear targets would be used, with pion beams of both charges. We would propose to use the small beam spot at LEP for energies up to 300 MeV, an energy range where absorption processes are thought to be understood. For higher beam energies, and thus very high nuclear excitations, we would also require time with the P^3 beam, up to 500 MeV. Altogether, we estimate that two weeks of beam time for data at each of these channels can give enough information to infer the expected very high nuclear excitations that pions may generate.

IX. PION ENERGIES ABOVE THOSE CURRENTLY AVAILABLE AT LAMPF

Extensions of investigations to energies above those currently available at LAMPF could be made with beams from the AGS or KEK, or with an application of developments in superconducting cavity technology, which is described below. Following this, we briefly indicate experiments with pions in this energy range that connect to physics issues whose importance was established earlier in this document. With boosts of energy with superconducting cavities, pion momenta up to 1 GeV/c or higher could be achieved. In addition to the topics mentioned below, one is referred to the document "Physics with PILAC" [27], which details a more extensive menu of physics with GeV pions.

LAMPF has very high-intensity beams of pions up to 300 MeV. This has made possible numerous pion-nucleon scattering and pion transport experiments at the $\Delta(1232)$ resonance. Experiments at the next-higher resonances, the $P_{11}(1440)$, $D_{13}(1520)$, and $S_{11}(1535)$, are possible at LAMPF using pion beams of energies up to the maximum energy of pions produced, approximately 630 MeV. However, the available pion intensity drops dramatically as the maximum energy is approached, more than a factor of ten in the region between 500 and 600 MeV. Experiments at the next-higher pion-nucleon resonances are difficult because of the low beam intensity and because it is not possible to get access to the high-energy part of these resonances, which are 100–200 MeV wide. Also, production of η mesons is limited, since the narrow maximum in the yield of η occurs at 624 MeV where the pion intensity is very low.

A pion accelerator, adding approximately 100 MeV, after the P^3 beam line would make a dramatic difference [28]. The intensity of the pion beam in the 500–600-MeV region would be increased by more than an order of magnitude, and the maximum pion energy would be raised to approximately 730 MeV. A beam line and linac design for a 125-MeV linac constructed with 7-cell 805-MHz cavities was presented at the Future Directions Meeting at BNL in March 1993 [29]. The necessary phase control for locking a high-Q superconducting cavity to pions produced by the LAMPF 201.25-MHz linac has already been demonstrated in use of the SCRUNCHER [30,31].

Recently, an 805-MHz 4-cell superconducting cavity was tested at Los Alamos [32]. This cavity achieved an energy gradient of 16.7 MeV/meter at a Q of greater than 3×10^9. This exceeded the gradient assumed in the linac design by a factor of 1.7. Eight of these cavities would produce 100-MeV energy gain. The performance of this linac would be better than the original design because of larger rf-bucket size and fewer pion decays, and the cost would be lower.

This "afterburner" need not be implemented in the form of a single large construction project. Instead, we suggest that it would make sense to build the cavities one or two at a time and add them to the P^3 channel as they become available. Indeed, it may be possible to install the cavities in horizontal cryostats made surplus by the shutdown of the GTA accelerator project at Los Alamos, thus minimizing the cost.

A. Baryon Resonances

Unique possibilities are provided by the pion to elucidate the role of the poorly known quark and gluon "condensates" in nuclei. We have already discussed this in connection with $\Delta(1232)$ dynamics in nuclei (Sect. IV). As stated there, the determination of baryon resonance properties in nuclei is important because the results can be used to study certain quark condensates that are at present unknown and have broad significance in nuclear and particle physics. Because of the special role played by the pion coupling to quarks and hadrons in general, pion interactions in nuclei may turn out to be as important as, or perhaps even more important than, the electromagnetic interaction for establishing QCD as the theory of nuclei.

For this reason, the physics of baryon resonances in the medium is an important focus for future research with pions. Just as in the case of the $\Delta(1232)$, it is important to identify experiments that can both distinguish a given resonance from competing background processes and at the same time allow a determination of the masses, widths, and coupling of pions and nucleons to the resonances in the nucleus. Excitation of baryon resonances, with subsequent detection of the decay products in coincidence, constitute one promising class of experimental measurements. This activity will require beams of $\pi^{\pm}$ in the 0.5–2-GeV region, and will benefit from coordinated experiments with electromagnetic probes, which are already providing some suggestions that medium modifications to masses and widths are quite important.

B. (π, η) and Kaon Reactions

Various measurements such as (π, η) and kaon-induced reactions allow one to focus on particular sets of resonances. The (π, η) reaction will help isolate the behavior of the the S_{11} baryon resonance in nuclei. The kaon-induced reactions, possible with yet higher energy beams, will enable one to explore quark condensates with strange probes.

APPENDIX: STRONG INTERACTION PHYSICS WITH PIONS AT LAMPF (SECTION OF LAMPF USERS GROUP WHITE PAPER)

The LAMPF high-intensity pion beams, with their capability for high-resolution studies, constitute a unique national resource, one which unfortunately soon may no longer be supported. With the demise of KAON we have lost the promise of seeing comparably intense secondary hadron beams made available for nuclear physics research. Now that the Defense Programs component of DOE has announced that it plans to operate the LAMPF accelerator at high intensity for nine months during the next few years, it is imperative that NSAC re-examine the question of supporting cost-effective experiments in Area A. We outline here the elements of two such key experiments with pion beams that would play a significant role in advancing our understanding of nuclear physics issues important not only to hadronic but also to electromagnetic and radioactive-beam physics. We also describe a third topic, that of pion dynamics, in which LAMPF has already played a major role in indicating possible future directions, and which is closely connected to the core CEBAF programs in the physics of few-nucleon systems and baryon resonances.

Fundamental πN and $\pi\pi$ Interactions

Precision tests of QCD follow from low-energy theorems based on chiral and isospin symmetries. These symmetries are broken because of non-zero quark masses and quark mass differences. New types of measurements of πN elastic and charge-exchange scattering are required to test and characterize the theory. In addition, an important method of determining the pion-nucleon coupling constant also relies upon low-energy πN data.

Chiral symmetry breaking in the π-N system relates directly to the sigma term (determined by analytically continuing physical amplitudes into unphysical regions) and the strangeness content of the nucleon. The extrapolation required is subject to uncertainty arising from inconsistencies between "old" and "new" low-energy data. Results obtained at LAMPF (and verified at TRIUMF and PSI) indicate that pre-meson-factory differential cross section measurements are in error by $\sim 25\%$ in the 30–50-MeV region. Moreover, the assumption of isospin invariance has recently been challenged by comparing data from πN elastic and charge-exchange scattering. A definitive set of charge-exchange measurements, including analyzing powers, is needed for energies < 100 MeV in order to address isospin symmetry breaking and to carry out the analysis leading to the sigma term. Only LAMPF among the meson factories has both the high intensity and the experimental facilities needed to perform the charge-exchange measurements.

Furthermore, it has recently been stressed that $\pi^{\pm}p$ scattering data in the Coulomb-nuclear interference region over the 50–500-MeV range are needed as input to dispersion relations. Such experiments are well matched to LAMPF capabilities. Similarly, the unique LAMPF resources of high-energy pion beams and the Neutral Meson Spectrometer provide the optimum facility to determine the fundamental $I = 2$ $\pi\pi$ s-wave scattering length from exclusive measurements of the $\pi^+p \rightarrow \pi^+\pi^0p$ cross section.

Exotic Nuclei

Precision spectroscopy of halo nuclei in which one probes the limits of the valley of stability is ideally matched to the pion double-charge-exchange (DCX) capability of LAMPF. The small cross sections demand high flux. Investigation of light nuclei such as ^{11}Li $\cdots$ ^{17}B pushes the N/Z ratio to extreme values in these exotic systems. The pion probe is complementary to radioactive-beam measurements, because pion reactions favor low angular momentum transfer. The cleanliness of the reaction makes possible the observation of low-lying excited states in these neutron-rich nuclei, which is difficult in heavy-ion studies. Furthermore, the sensitivity of the pion DCX cross section to the assumed size of the halo is sufficiently strong (falling roughly as the 6^{th} power of the radius) that, even allowing large uncertainties in the calculations, significant constraints can be placed on the halo size.

A straightforward reconfiguration of one of the beam channels at LAMPF would make it possible to use the beam's time structure to determine the energy of the incoming pion, replacing the more usual momentum analysis. Using an existing spectrometer, with a time-of-flight "wall" behind the focal plane, would result in an increase by a factor of 30–1000 in the counting rate over that available with the present system, thus providing a timely and cost-effective way to perform precision spectroscopic measurements that will play an important role in defining the structure of exotic nuclei.

Future Directions: Pion Dynamics

Few-nucleon systems play a key role at CEBAF and LAMPF in studies of hadron dynamics, because the reactions are less contaminated by multiple scattering than those in larger nuclei. Nuclear structure issues are also under control since they are amenable to study using exact (*e.g.*, Faddeev or Monte Carlo) methods. Moreover, the pion and photon couplings to hadrons are *complementary*: Because photons couple via vector meson (ρ, ω) dominance, pseudoscalar pions provide a picture of hadron excitations complementary to that which will be seen at CEBAF.

By using the intense high-energy pion beams at LAMPF to observe scattering without and with charge exchange, one can isolate isoscalar and isovector properties. For example, the ^{3}He(π^-, π^0) single-charge-exchange (SCX) reaction utilizing the Neutral Meson Spectrometer and $\pi^\pm$ scattering from polarized ^{3}He can probe isovector and isoscalar form factors. Multiple scattering effects can be understood, by comparing π^- scattering from ^{3}He in which they are small with π^+ scattering in which they dominate.

Determining the medium influence on the $\Delta_{33}(1232)$ resonance was pioneered at the meson factories. Investigating this and other baryon resonances in the strong field of the nuclear medium provides the means to elucidate their structure. Detailed understanding will require a combined effort with both hadronic and electromagnetic probes. Of the meson factories, only LAMPF is capable of beginning work in the $P_{11}(1440)$, $D_{13}(1520)$, and $S_{11}(1535)$ resonance regions.

Additionally, elucidating the relationship between the properties of hadrons and the quark/gluon vacuum condensates of nonperturbative QCD and QCD sum rules requires high-energy pion probes. Properties of baryon resonances and their coupling to pions provide empirical constraints on the "four-quark" condensates that are fundamental but poorly known properties of the nucleus. The probability with which non-nucleonic components appear in nuclear wave functions is a consequence of these condensates. Recently, LAMPF experiments on the $(\pi^+, \pi^\pm p)$ and $(\pi^\pm, \pi^0 p)$ reactions have indicated that the Δ_{33} probability in nuclear ground states is measurable, leading to a re-emergence of experimental and theoretical interest in this question. Several different measurements utilizing newly developed capabilities at LAMPF have been proposed with the aim of a quantitative exploration of the presence of Δ's within nuclei.

Finally, deep inelastic pion scattering experiments at LAMPF in the 400–600-MeV region have uncovered large discrepancies between experiment and standard intranuclear cascade (INC) models: both the quasi-elastic peak and the large energy-loss portions of the spectrum are well reproduced by the INC calculations, *but* cross sections in the region of final pion energies that strongly excite the Δ_{33} are a factor of 5–10 larger than theoretical predictions. High-energy pions are required to probe in detail this unexplained aspect of pion-nucleus interactions. Such information will provide important input to the interpretation of results obtained at RHIC.

REFERENCES

[1] W. R. Gibbs and W. Kaufmann, Ann. Phys. (N.Y.) **214** (1992) 84, and to be published.

[2] R. Timmermans, private communication.

[3] G. Höhler, "Tests of Predictions from Chiral Perturbation Theory for πN Scattering," Talk presented at MIT Workshop—Chiral Dynamics: Theory and Experiment, July 1994. To be published in Lecture Notes in Physics, Karlsruhe preprint TTP 94-23.

[4] G. Höhler, "How Can the Accuracy of the Determination of the Sigma Term from πN Scattering Data be Improved?," Karlsruhe preprint TTP 94-25, October 1994.

[5] P. Baillon *et al.*, Nucl. Phys. **B105** (1976) 365–430; CERN 75-10, Laboratory I, Track Chambers Division (September 1975).

[6] U. Wiedner *et al.*, Phys. Rev. Lett. **58** (1987) 648; Phys. Rev. **D40** (1989) 3568.

[7] C. Joram *et al.*, to be published.

[8] A. A. Bolokhov *et al.*, Nucl. Phys. **A530**, 660 (1991).

[9] D. Pocanic, unpublished.

[10] R. Bilger *et al.*, Z. Phys. **A343** (1992) 491.

[11] R. Bilger, H. A. Clement, and M. G. Schepkin, Phys. Rev. Lett. **71** (1993) 42.

[12] M. A. Kagarlis and M. B. Johnson, Phys. Rev. Lett. **73** (1994) 38.

[13] T. Goldman *et al.*, Phys. Rev. **C39** (1989) 1889.

[14] H. Clement *et al.*, Phys. Lett. **B337** (1994) 43.

[15] M. A. Shifman, A. I. Vainshtein, and V. I. Zakharov, Nucl. Phys. **B147** (1979) 385.

[16] V. M. Belyaev and B. L. Ioffe, Sov. Phys. JETP 56 (1982) 493.

[17] L. J. Reinders, H. R. Rubinstein, and S. Yazaki, Nucl. Phys. **B213**, 109 (1983).

[18] E. G. Drukarev and E. M. Levin, Pis'ma Zh. Eksp. Teor. Fiz. **48**, 307 (1988); Nucl. Phys. **A511**, 679 (1990); Prog. Part. Nucl. Phys. **27**, 77 (1991).

[19] T. D. Cohen, R. J. Furnstahl, and D. K. Griegel, Phys. Rev. Lett. **67**, 961 (1991); R. J. Furnstahl, D. K. Griegel, and T. D. Cohen, Phys. Rev. **C46**, 1507 (1992); X. Jin, T. D. Cohen, R. J. Furnstahl, and D. K. Griegel, Phys. Rev. **C47**, 2882 (1993).

[20] E. M. Henley and J. Pasupathy, Nucl. Phys. **A556**, 467 (1993).

[21] M. B. Johnson and L. S. Kisslinger, LAMPF preprint (1994).

[22] W. R. Gibbs and A. C. Hays, Phys. Rev. Lett., **67** (1991) 1395.

[23] H. A. Thiessen, J. F. Amann, R. L. Boudrie, C. L. Morris, and J. D. Zumbro, unpublished.

[24] C. M. Chen, D. J. Ernst, M-F. Jiang, and M. B. Johnson, in preparation.

[25] J. D. Zumbro *et al.*, Phys. Rev. Lett. **71** (1993) 1796.

[26] W. Benenson, D. J. Morrissey, and W. A. Friedman, Annu. Rev. Nucl. Part. Sci. 44 (1994) 27.

[27] "Physics with PILAC," Los Alamos Document, LA-UR-92-150 (1991).

[28] R. L. Boudrie, C. L. Morris, B. Rusnak, H. A. Thiessen, and J. D. Zumbro, unpublished.

[29] J. D. Zumbro, "η Production at the LAMPF P^3 Channel," BNL-52389, March 1993, pp. 557–567.

[30] J. D. Zumbro, H. A. Thiessen, C. L. Morris, and J. A. McGill, *Nucl. Instrum. Methods* **B40/41** (1989) 896.

[31] J. M. O'Donnell *et al.*, *Nucl. Instrum. Methods* **A317** (1992) 445.

[32] Brian Rusnak *et al.*, to be published.