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EXPERIMENTAL STUDIES OF NUCLEON-NUCLEON AND PION-NUCLEUS INTERACTIONS AT INTERMEDIATE ENERGIES

ABSTRACT

We are applying for a three-year grant from the U. S. Department of Energy to New Mexico State University to continue its support of our work on experimental studies of nucleon-nucleon and pion-nucleus interactions at intermediate energies, which has been carried out in collaboration with groups from various laboratories and universities. The nucleon-nucleon work is aimed at making measurements that will contribute to a determination of the isospin-zero amplitudes, as well as continuing our investigations of evidence for dibaryon resonances. It is based at the LAMPF accelerator in Los Alamos, New Mexico. Current and planned experiments include measurements of total cross-section differences in pure spin states and of spin parameters in neutron-proton scattering. The pion-nucleus work is aimed at improving our understanding both of the nature of the pion-nucleus interaction and of nuclear structure. It consists of two programs, one based at LAMPF and one based principally at the SIN laboratory in Switzerland. The LAMPF-based work involves studies of large-angle scattering, double-charge-exchange scattering, including measurements at a new energy range above 300 MeV, and a new program of experiments with polarized nuclear targets. The SIN-based work involves studies of quasielastic scattering and absorption, including experiments with a new large-acceptance detector system planned for construction there. We are requesting support to continue the LAMPF-based work at its current level and to expand the SIN-based work to allow for increased involvement in experiments with the new detector system.

I. INTRODUCTION

We are applying for a grant from the U. S. Department of Energy to New Mexico State University to continue its support of our work on experimental studies of nucleon-nucleon and pion-nucleus interactions at intermediate energies. The period of support requested is for three years, beginning January 1, 1988, immediately following the expiration of the present contract.

For nearly ten years, the DOE has supported our research in these two fields at the LAMPF facility of the Los Alamos National Laboratory at the level of one faculty member, George R. Burleson, two Postdoctoral Associates stationed at LAMPF, and graduate and undergraduate students. The two Postdoctoral Associates currently are Kalvir S. Dhuga and John A. Faucett; Kalvir Dhuga will be replaced with Sanjoy Mukhodaphay beginning September, 1987. About three years ago, the contract was expanded to support additional research in pion-nucleus interactions which has been based principally at the SIN laboratory near Zurich, Switzerland, with some work at the TRIUMF laboratory in Vancouver, Canada, when a new faculty member, Gary S. Kyle, joined the group. No additional non-faculty personnel were requested for this program at that time. All of this work has been a collaborative effort with physicists from various laboratories and universities.

Plans are now in progress at SIN for a new, long-term program of pion absorption studies, based on a new large detector system financed principally by SIN, with a collaboration that includes NMSU. Our pion-nucleus studies at LAMPF are now moving in two new directions, toward research at energies above the $\Delta(3,3)$ resonance and toward studies with polarized nuclear targets, a field which represents a major commitment from the laboratory. The nucleon-nucleon research at LAMPF includes work in progress that is scheduled to continue through 1988 and probably beyond. Accordingly, we are requesting an increase in the level of support for the NMSU program for the work at SIN, to include one more Postdoctoral Associate, who would be stationed at SIN, plus some additional equipment and travel funds. We are also requesting that our LAMPF-based programs be maintained at the current level. With some exceptions, the work at LAMPF would then be primarily the responsibility of Burleson and two Postdoctoral Associates there, with some participation by Kyle, as is currently the case. The work at SIN would be primarily the responsibility of Kyle and one Postdoctoral Associate there, with some participation by others in the group.

A discussion of the physics of these programs is given below, together with information on their history, their present status, and plans for the future.

II. NUCLEON-NUCLEON STUDIES

The nucleon-nucleon (NN) interaction is an important fundamental reaction, which should be better understood than it now is. Due largely to the new proton-proton (pp) data that have accumulated during the past several years, the five isospin-one (I=1) amplitudes describing this interaction have been fairly well determined up to about 800 MeV. Phase-shift studies[1-5] of these data have found structure in certain partial waves that have suggested the possibility of the existence of dibaryon resonances. Evidence for these resonances has been sought in other reactions, but the situation as of now is not clear.[6] It is important, however, to theories of fundamental particles to establish whether they exist or not. For the I=1 channel, this question is clouded by the presence of the NΔ inelastic channel. This problem does not exist in the I=0 channel, however, which is found in neutron-proton (np) scattering (which consists of equal parts of I=0 and I=1).

The situation with the I=0 channel is different from that of the I=1 channel, in that the amplitudes are very poorly determined above about 500 MeV.[1-5] The reason for this is not hard to find. Experiments with neutrons are much more difficult than those with protons, and the data are consequently characterized by apparent inconsistencies among different sets of results. The number of np experiments that have been carried out is also much smaller, and the precision obtained in the results is generally poorer than for pp scattering. Neutron beams generally contain a broad spectrum of energies and are of a lower intensity than proton beams. The detection of neutrons is also more difficult than for protons.

There are several reasons for studies of the I=0 NN scattering amplitudes. One, as mentioned above, is the fundamental nature of the interaction. It is important to determine both isospin amplitudes in order to test any theoretical description of the NN interaction, including both meson exchange and quark models. A comparison of the I=1 and I=0 channels should also be instructive; for example, the $pp \rightarrow N\Delta$ and $pp \rightarrow \pi d$ inelastic channels have a strong influence on the I=1 amplitudes but are absent in the I=0 channel. Another reason for such studies is that both channels are used as inputs to models of the proton-nucleus interaction, such as those that use Dirac phenomenology.[7-10] Some of the discrepancies seen between theory and experiment here may result, for example, from the poor knowledge of the I=0 amplitudes. Finally, there is the question of dibaryon resonances. Evidence of structure in $\Delta\sigma_L$(I=0), the total cross section difference between parallel and antiparallel initial spin states, was derived from measurements of $\Delta\sigma_L$(pd).[11] Further studies are needed to investigate this, involving direct measurements with neutrons, in order to clarify the nature of the structures found in both isospin systems.

Current Experiments. For several years, we have been involved in measurements of spin correlations in NN scattering at LAMPF, with Argonne National Laboratory as a major collaborator. After several pp experiments, we began work on studies of np interactions. The first of these was Experiment No. 665/770, "The Measurement of np Elastic Scattering Spin Correlation Parameters with L- and S-Type Polarized Beam and Target between 500 and 800 MeV," Argonne, LANL, Texas A & M, University of Montana, Washington State, and NMSU; H. Spinka, Argonne, and G. Burleson, Spokesmen. In this work, we have made measurements of the initial spin correlation parameters C_{LL}, C_{SS}, and C_{LS} at center-of-mass angles between 36° and 172° at energies of 500, 650, and 800 MeV, with some measurements at other energies. This experiment ran for three years and accumulated rather copious amounts of data, which are now being analyzed by members of the Argonne group and by two NMSU graduate students, who will use the results for Ph.D. theses. The statistical precision of the final results should generally be better than ± 0.1. Preliminary results have been submitted for publication.[12] We expect the analysis of all the data to extend beyond 1988. As expected, the results so far agree generally well at 500 MeV with phase-shift predictions but indicate differences at higher energies.

Another major activity now in progress is Experiment No. 960, "Measurements of the Total Cross Section Difference in Neutron-Proton Scattering for Longitudinally Polarized Beam and Target," same collaboration as above; K. Johnson, LANL, L. Northcliffe, Texas A & M, and G. Burleson, Spokesmen. In this work, we are measuring the quantity $\Delta\sigma_L(np)$ at energies between 300 and 800 MeV. The experimental method involves detecting polarized neutrons scattered from a polarized proton target in a hodoscope of long, thick neutron counters located downstream of the target. The cross section differences are found by the usual method of extrapolating the scattering angular distribution to the forward angle. Charged particles are rejected by an anticoincidence counter located just upstream of the hodoscope. Time-of-flight methods are used to select neutrons of the primary beam energy, together with the new buncher/chopper system at LAMPF. Fast timing circuits developed at Argonne are used to give position information on the particles detected in each neutron counter. Coincidences between the perpendicular counter arrays are also used as an additional method of obtaining this information, so that two partly independent determinations of $\Delta\sigma_L(np)$ are made. Monitoring is carried out in the primary proton beam. The precision expected is ± 0.5 mb at 800 MeV and ± 1 mb at lower energies. In 1987, we have been scheduled for three or four of the seven beam energies that have been approved, and we expect to run the remaining energies in 1988. This experiment is the basis of a Ph.D. thesis for an NMSU graduate student.

Future Plans. The plans for work beyond this experiment depend on several questions. We have proposed using the same experimental setup, with a transversely polarized proton target, to measure the analogous quantity $\Delta\sigma_T(np)$, for transverse beam and target polarizations. This experiment would require the continued participation of the Argonne group, a question that has not as yet been resolved. It would also require the availability of a neutron beam that is not too intense, since our previous work in measuring total cross sections has indicated that experimental difficulties are found at high rates. LAMPF is now working on the installation of a new high-intensity polarized proton source, which would produce a high-intensity polarized neutron beam. Current expectations are for it to be ready near the end of 1988. Early successful operation of the source in its highest-intensity mode might lead to a laboratory decision not to continue immediately on any low-intensity work with neutron beams, so that this measurement might be postponed or dropped.

When the new source is operating, one of the first experiments currently expected to run is one in which both we and Argonne have been invited to participate, Experiment No. 876, "Spin Transfer Measurements for np Elastic Scattering," originally a collaboration among LANL, University of Texas, and UCLA; M. McNaughton, LANL, Spokesman. This involves measurements of the np elastic spin transfer parameters K_{SS}, K_{LS}, K_{SL}, and K_{LL} at 650 and 800 MeV. The experiment is performed with a polarized neutron beam incident on a liquid hydrogen target. The spin of the outgoing proton is measured with a carbon polarimeter. In order to measure an outgoing L-type proton spin for K_{SL} and K_{LS}, the proton trajectories would be bent in a magnet so as to precess the proton spin by 90°. It should be possible to measure these parameters to a statistical precision of ± 0.03 over an angular range of 50° to 180° in several weeks of beam time.

If, after this work, it appears that additional np measurements are necessary for a determination of the I=0 amplitudes with a quality about equal to that of the I=1 amplitudes, we would want to continue working on this problem.

III. PION-NUCLEUS STUDIES AT LAMPF

Pion-nucleus studies have been active fields of research at the meson factories (LAMPF, SIN, AND TRIUMF) for more than a decade.[13] The attraction of this work lies in the observation that since we have a detailed understanding of the pion-nucleus interaction at energies of up to 500 MeV or higher, as well as much detailed information on the structure of nuclei, the experimental results can be used to test how well these two pieces of knowledge can be fit together, and, more importantly, what can be learned that is new.

There are many attractive features of pions for these investigations. The pion is the lightest of the mesons, and as such it is responsible for the long-range part of the NN interaction. It exists in three charge states and carries one unit of isospin. At energies between 100 and 300 MeV, the pion-nucleon interaction is dominated by the formation of the $\Delta(3,3)$ resonance. This means that the π^+p (π^-n) interaction is much stronger than the π^-p (π^+n) interaction, so that differences in neutron and proton behavior in the nucleus can be more easily seen with pions than with any other probe. At these energies, the pion-nucleus interaction is very strong, but at both lower and higher energies it is much weaker, so that the extent of its penetration into the nucleus varies with energy. The different charge states permits careful study of Coulomb effects and also allows single and double charge exchange scattering to take place, both to analog and nonanalog states. Since double charge exchange involves two nucleons, it is sensitive to nucleon-nucleon correlations in the nucleus. Moreover, since the pion is a Boson, it can be absorbed and emitted singly in nuclear interactions, in processes involving large energy transfers that lead to a range of final states.

The pion-nucleus interaction has been under much discussion at LAMPF and other places recently. It was the subject of a one-day session held at LAMPF in August, 1986, in conjunction with a meeting of the Program Advisory Committee (PAC). This led to the scheduling of a one-week workshop at LAMPF on future directions in pion-nucleus physics in August, 1987. (NMSU personnel have been invited to give three talks at this conference.) It has been noted that a substantial body of experimental data now exists on the full range of pion-nucleus reactions. Much progress has been made in formulating a theoretical understanding of the basic pion-nucleus interaction, but a full treatment does not yet exist and is a very difficult challenge. It is not clear whether all the major features of the interaction, such as spin dependence, have yet been satisfactorily addressed. For much of the data, such as double charge exchange, there is really no good explanation as yet. The role of Δ-formation and propagation in the nucleus is clearly central to the interaction in the 100-300 MeV region, but the relation of this picture to other microscopic calculations is not clear. For scattering at large angles, the unexpected magnitude of the cross section and the $\pi^{\pm}$ differences found there at some energies are not yet understood. Pion quasielastic scattering, which is sensitive to the pion-nucleus interaction in the nuclear medium, is only partly understood. Pion absorption is also not fully understood and probably contains new and important physics.

Current Work. For many years, we have been involved in studying the pion-nucleus interaction in regions where it is least explored, in hopes of discovering new phenomena and increasing our knowledge of this process. One of these fields of study is the double charge exchange (DCX) reaction, leading to both analog and nonanalog final nuclear states. This reaction has been found to have fairly simple systematic features in its angular distributions, energy excitation functions, and dependence on atomic number A. Theoretical studies of these results have included partly-phenomenological coupled-channel models, phenomenological two-amplitude models, models which emphasize particular types of reactions mechanisms, and models that involve certain aspects of nuclear structure. The present status of this field has been summarized recently.[14,15]. While much progress has been made in understanding this process, additional work, both experimental and theoretical, remains to be carried out before, for example, the goal of extracting information on NN correlations in the nucleus can be reached.

As part of our continuing study of this process, we are involved in three DCX experiments that are scheduled to run on EPICS in fall, 1987. This work involves a collaboration with LANL, the University of Pennsylvania, and the University of Texas. The results of these may lead us to propose additional experiments on EPICS. We are also involved in a new program of DCX measurements at energies above 300 MeV, which is described below.

Another field of study in which we have concentrated is large-angle scattering, in which we have collaborated with LANL, the University of Minnesota, the University of Texas, and the University of Pennsylvania. This involved developing a modification of the EPICS spectrometer system at LAMPF to allow extending its angular range to 180°.[16] Experimental results have found the large $\pi^{\pm}$ differences mentioned above, as well as suggestions of energy-dependent modifications of the pion-nucleus interaction due to the nuclear medium, as seen in optical model calculations.[17] More theoretical work on these results using microscopic models of the pion-nucleus interaction is in progress, in collaboration with D. Ernst, Texas A & M. This involves, for the first time, a careful comparison of the Δ-hole model[18] and the relativistic field-theoretical model of Ernst and co-workers.[19] We believe that this work may lead to a definitive theory of elastic pion-nucleus scattering. The results of this work may lead us to propose further experiments at EPICS on large-angle scattering. We note, for example, that no such measurements have been made at LAMPF on non-self-conjugate nuclei or on nuclei with non-zero spin.

Experiments with Polarized Nuclear Targets. At LAMPF, we are beginning work on two new programs of studies of pion-nucleus interactions. One of these involves the use of polarized nuclear targets. The idea for this began several years ago with the realization by D. Hill of Argonne that the non-spin-zero nuclei in polarized proton targets are actually polarized themselves at a sufficiently high level that they might be useful as targets. Work at Argonne by Jarmer, et al,[21] later showed that a polarized ^{13}C target was feasible. This led to the first proposal at LAMPF for scattering from such a target, with polarized protons as the beam, using the HRS spectrometer system. This is Experiment No. 955, "Polarized Proton Scattering from Polarized Nuclear Targets," University of Texas, LANL, University of Minnesota, Ohio State, IBM, Rutgers, University of South Carolina, Arizona State, and NMSU; G. W. Hoffman, R. L. Ray, and M. L. Barlett, Texas, and J. Jarmer, LANL Spokesmen. The physics objective here is to study what can be learned in general by introducing a new degree of freedom into the medium-energy scattering problem and, in particular, to test the new Dirac phenomenology that has been used to describe proton-nucleus interactions.[7-10] Theoretical predictions of some of the results that might be found from this investigation have been discussed and published.[22,23]

Further considerations about the physics of scattering from polarized nuclear targets were discussed in a workshop on this subject which was held at LAMPF in February, 1986.[23] At this meeting, presentations were given on problems of the targets themselves, as well as on studies involving proton, pion, and electron scattering from such targets. The discussions here confirmed an intuitive feeling that there is much important physics to be learned from such studies. For pion work, we note that differential and total cross sections are related to sums of squares of amplitudes, but that scattering asymmetries from polarized targets are related to the interference between amplitudes, a quantity that is very sensitive to details of the amplitudes. Any model of pion-nucleus interactions that is serious enough to address the question of spin dependence must confront the results of such measurements. These include, in particular, the Δ-hole model[18] and the field-theoretic model of Ernst, et al.[19] For the Δ-hole model, one subject of interest which this work is sensitive to is the question of the strength of the spin-orbit interaction of the Δ in the nucleus. Predictions of the asymmetries to be found in these experiments have been made,[23] but these are probably not very reliable in detail at this stage.

We have submitted two complementary proposals to the LAMPF PAC for measurements of pion scattering from polarized nuclear targets. These have both been approved, and they should begin running in 1989. (The HRS experiment above is scheduled to run in 1988, so that it will be the first such experiment at LAMPF.) One of the pion proposals is Experiment No. 1025, "Pion Elastic and Inelastic Scattering from Polarized ^{13}C," LANL, Minnesota, Texas, Pennsylvania, Arizona State, and NMSU; D. Dehnhard, Minnesota, and G. Burleson, Spokesmen. This was approved by the EPICS Subcommittee of the PAC with an A^+ rating, the highest they have ever given. In this experiment, we plan to measure the asymmetry in $\pi^\pm$ elastic and inelastic scattering from polarized ^{13}C at 162 MeV, 30^o to 100^o, where there is existing cross-section data.[24] A new target magnet and dilution refrigerator system constructed by LAMPF will be used, with the EPICS spectrometer system. Since the target will be of the frozen-spin type, a new magnet to provide a holding field will have to be designed and constructed. A modification of the EPICS system will also be necessary in order to mount the target system. One cycle of running time (about 1200 hours) has been approved; this should give statistical errors of less that ± 0.1 on all data, except for some excited states in certain angular regions.

The other pion proposal is Experiment No. 1023, "Analyzing Power Measurements for the (π^+,π^0) Reaction on a Polarized ^{13}C Target," LANL, Arizona State, Maryland, Texas, Stanford, TRIUMF, and NMSU; J. Comfort, Arizona State, and G. Kyle, Spokesmen. This experiment was approved by the LEP Subcommittee of the PAC with a rating of A, again one of the highest given. In this work, we will measure the analyzing power for this reaction, leading to the isobaric analog state in ^{13}N, at 164 MeV. The detector used will be the existing LAMPF π^0 spectrometer, and it will cover the angular range from 15^o to 75^o, where the several maxima in the analyzing power are expected to be found. A beam time of 740 hours has been approved, which should again give statistical errors less than ± 0.1. The experiment will be run in the LEP channel. Because the beam spot is smaller here than at EPICS, a simpler target system can be used, one similar to that planned for the HRS experiment.

Experiments at Energies above 300 MeV. The other new program is a projected set of studies of DCX scattering, and possibly other interactions, at energies above the Δ resonance, roughly 300-550 MeV. The initial work is Experiment No. 1028, "Measurements of Double-Charge-Exchange and Elastic Scattering on ^{14}C and ^{16}O at Energies above the Δ Resonance," LANL, Pennsylvania, Texas, Tel Aviv University, Argonne, Texas A & M, and NMSU; H. W. Baer and C. L. Morris, LANL, and G. Burleson, Spokesmen. This is currently scheduled to run late in 1987 on the P^3 Channel, and preparations for it are under way. Necessary hardware changes include the use of a new pion production target for the channel, to improve its energy resolution; modifications of the Large Aperture Spectrometer which is to be used for this work, including additional counters and wire chambers and provision for using a sweeping magnet; and the construction of a gas threshold Cherenkov counter designed by us to reject electrons, which are copiously produced at small angles.

The physics motivation for this experiment is based on recent theoretical results on the DCX interaction at energies on and below the Δ resonance. These studies represent various pictures of the dynamics, including six-quark bags,[25] Δ-N interactions with one-gluon exchange,[26] DCX on meson-exchange currents,[27] multiple-scattering theory with π-N form factors,[28] and optical potentials with higher-order terms.[29] Though these use different languages, they all seem to indicate that a sizeable contribution to this process arises from a localized region of the nucleus, of size typically 1 fermi. Since this value is close to the rms radius of a nucleon, the suggestion is that the DCX reaction may be probing possible contributions to nuclear interactions arising from such things as deconfinement or quark-sharing mechanisms.

The energy region above 300 MeV seems to be a fruitful place for further studies of these possibilities. Here, the total π-N cross sections are considerably smaller than in the Δ resonance region and are fairly flat, allowing for a greater penetration into the nucleus. Pion absorption appears to play a smaller role, and pion production cross sections are also small, compared to elastic scattering, leading to a simplification of the pion-nucleus dynamics. The pion wave length is shorter, which should allow for greater sensitivity to any granularity of the nucleus. Finally, the expansion parameter for the π-N multiple scattering series, which is related to some of these quantities, is considerably smaller than on the Δ resonance (its value is about 0.53 at 180 MeV, and about 0.07 at 500 MeV). This means that theoretical calculations of the pion-nucleus interaction at these energies should be much simpler, since triple- and higher-order scatterings will play a smaller role. This region is also dominated to a certain extent by the N*(1440) resonance, which represents about half of the isospin one-half strength. For such a resonance, the relative strengths of the π^+p (π^-n) and π^+n (π^-p) interactions are reversed from what is seen with the Δ resonance. All of these considerations strongly suggest that much can be learned from studies of the pion-nucleus interaction at these energies.

In this experiment, we plan to measure small-angle cross sections for DCX scattering to both analog and nonanalog states at energies between 300 and 500 MeV. Predictions for the analog results, which are qualitatively different from each other, have been made by Liu and Franco,[30] using Glauber multiple-scattering theory, by Ernst,[31] within the field-theoretic model, and by Miller,[32] using a six-quark cluster model. No reliable predictions of nonanalog cross sections exist, but it is important to measure these in order to find an indication of the strength of transitions to nonanalog intermediate states in analog scattering. We note that between 50 and about 200 MeV, these strengths are comparable.[33] We also plan to measure elastic scattering cross sections on ^{16}O in this energy region. This should serve as a check on how well these can be calculated theoretically and will provide a constraint on calculations on DCX, as well as on single charge exchange, which has recently been measured on several nuclei in this energy region.[34]

We feel it likely that the results of this experiment will lead us to propose additional studies at these energies. These could include, for example, DCX studies with other nuclei, measurements of DCX angular distributions, or possibly additional measurements of elastic of inelastic scattering. We note that the availability of pion beams in this energy range which can be used for studies of this type is unique to LAMPF.

IV. PION-NUCLEUS STUDIES AT SIN

We plan to continue our studies of pion-nucleus absorption and quasielastic scattering at the Swiss Institute for Nuclear Research (SIN), with some work at LAMPF, during the period of 1988-90. To date we have concentrated on studies of the simplest pion-nucleus reaction channels at energies where the pion-nucleon interaction is dominated by formation of the Δ(1232) resonance, in order to build up a more complete experimental picture of the basic quasi-free pion-nucleus interactions. The success of these coincidence measurements has been due, in part, to the very favorable experimental environment of SIN, where a separated, continuous pion beamline (πM1) and a bread-ranged, moderate-resolution, magnetic spectrometer (SUSI) have been constructed. These exclusive data can usually be understood most easily with theoretical models; moreover, carefully-chosen studies of related isospin channels or different nuclear isotopes have often revealed interesting physics, independent of comparisons with theory. It should also be mentioned that while the major thrust of this work has been toward a unified understanding of pion-nucleus interactions in terms of the basic pion-nucleon and delta-nucleon interaction, quasi-free reactions may also be exploited to study important aspects of nuclear structure. Unlike transfer reactions, the kinematic and isospin selectivities of quasi-free reactions may be used to distinguish the effects of reaction dynamics and nuclear structure, both conventional and exotic. Some examples are seen in the studies of pion absorption[35] described in our current progress report.

From the first results of our own work and the body of related experiments, it has been clear that further progress toward a unified, microscopic understanding of the pion-nucleus interaction, and the realization of the full utility of quasi-free reactions as a probe of nuclear structure, will only be obtained from studies either of pion reactions to weak isospin channels or of those leading to large-multiplicity final states using a large-acceptance detector system (LADS). NMSU has been involved from the beginning in a proposal to build a LADS at SIN, as well as another proposal involving a less ambitious detector array, which are described more fully below and in Appendix A. These proposals will provide the basis over the forseeable future for our activities at SIN.

The motivation for the LADS comes from the body of experimental work in pion-nucleus scattering and reactions, and, in particular, the results of recent coincidence measurements of pion-nucleus reactions by groups at SIN and the other meson facilities. For several years, we have studied the simplest pion-nucleus reaction channels in helium and oxygen isotopes. These include quasi-free scattering and single charge exchange, which are related by isospin symmetry, quasi-free multiple scattering and double charge exchange, which are similarly related, and pion absorption. There have been some theoretical successes in describing these data in terms of fundamental interactions in the nucleus. Most notably, the delta-hole model has been extended to treat a variety of pion-nucleus reactions and scatterings in terms of the basic pion-nucleon (π-N) and delta-nucleon (Δ-N) interactions, and thus has given hope that a consistent microscopic theory of many pion-nucleus interactions may ultimately be attained. For example, cross section ratios for the reactions $^{16}O(\pi^{\pm},\pi^{\pm}p)^{15}N$ and $^{16}O(\pi^{+},\pi^{0})^{15}O$ were found to be strongly modified by the nuclear medium, most strikingly for the weakest, π^{-}-induced reaction, where reductions of the cross section by large factors were observed at the peak of the quasi-free kinematics,[36-38] an effect confirmed by others.[39] These modifications were predicted to arise from the interference of the direct pion-induced knockout with the delta-induced knockout amplitude[40,41] and were particularly sensitive to the strengths of the Δ-N interaction in isospin I=1 and I=2 states. At the same time, certain puzzles remain, among which is the strong s-wave repulsion term required in the pion-nucleus optical potential. This effect, which becomes most apparent in pion-nucleus scattering at low energies or at large angles,[20] may have its origin in the processes of pion absorption, but it has been given no theoretical basis as yet. Another major puzzle is the behavior of coherent double charge exchange as discussed above. Studies of quasi-free double charge exchange may help clarify the role of non-quasi-free modes. Our comparison[42] of the inclusive reactions $^{16,18}O(\pi^{\pm},\pi^{\pm})$ and $^{16,18}O(\pi^{\pm},\pi^{\mp})$ showed some deviations from expected isotopic ratios which hinted at an inconsistency between the DCX and the multiple scattering channels. The essential exclusive measurements could be made using a pion spectrometer such as SUSI with a LADS to analyze the coincident nucleons.

The effects of pion absorption are manifested in all pion-nucleus interactions. The simplest pion absorption process involving nucleon pairs (2N) results in the familiar ρ^2-term in the pion-nucleus optical potential and couples strongly to the Δ-N interaction in I=1 states. Pion absorption also results in a large energy transfer to the nucleus, which may probe the short-distance behavior of the nuclear wavefunction, particularly in channels where delta formation is not dominant. The 2N absorption process has been studied by several exclusive experiments in recent years. Absorption on both isoscalar and isovector pairs has been studied[43-45] for ^{3}He. The dominance of the absorption on isoscalar pairs, so-called quasi-deuteron absorption, is observed as a rather striking signature of a Δ-dominated process. However, a substantial and rather constant fraction (about 30%) of the total absorption over the resonance goes off the quasi-free 2N kinematics and appears to follow three-nucleon phase space. In heavier nuclei it is necessary to consider stronger effects of initial and final state interactions, but it appears that smaller fractions of the total absorption may be attributed to a quasi-deuteron absorption process. Our studies of ^{16}O(π^+,pp)^{14}N at 115 MeV[46] and LAMPF studies of ^{58}Ni(π^+,pp)^{56}Co at 165 MeV[47] suggest that less than 50% of the absorption arises from a quasi-deuteron process. Thus, it is clear that a large fraction of the total absorption must arise from some more complex, possibly exotic, mechanisms. One multi-nucleon mechanism, proceeding via the formation of "double-delta" intermediate states and, thus, resulting in a four-nucleon final state, has been prominently discussed.[48,49] It has also been suggested[50] that nucleon removal due to hard Δ-N interactions may be an important process. These models make different predictions about the multiplicities and energy dependences to be observed.

Most experimental studies of the 2N absorption process have utilized two-arm coincidence techniques, where the relatively small detectors are scanned to cover phase space, which results in systematic errors and inefficient utilization of beam time. Even with complete kinematic information for two outgoing protons, the quasi-deuteron absorption cannot be separated without invoking some model for the multi-nucleon "background" processes. The poor quality of data for absorption on isovector nucleon pairs in ^{3}He and the absence of such exclusive data for heavier nuclei is due to the weakness of the reactions, the inefficiencies of neutron detection, and the two-arm experimental technique. Experiments using a detector having complete solid-angle coverage would improve data-taking rates by orders of magnitude, thus, advancing even our knowledge of the 2N absorption process.

A few recent experiments, some with NMSU participation, have attempted to directly determine the role of multi-nucleon absorption from measurements of the $(\pi^{+},3p)$ reaction. All these experiments are deficient in solid-angle coverage, and some have large uncertainties in proton energy calibrations; thus the results have been inconclusive. Using the requirement of a fast backward proton coincident with two forward protons to discriminate against contributions of hard initial or final state interactions to the $^{16}O(\pi^{+},3p)^{13}C$ reaction, we have attempted to determine the total 3N absorption to low-lying states of

^{13}C. The cross section, extrapolated according to 3N phase space, was about 20 mb, or 10% of the total absorption at 115 MeV.[51] Recently, a large yield at low missing energy has also been observed by Bauer[52] for 65 MeV π^+ on ^{16}O. However, much smaller fractions were reported for $^{12}C(\pi^+,3p)X$ by Tacik[53] at 228 MeV and by Brueckner[54] at 290 MeV, who suggest that much of the absorption goes into 4N final states with an unobserved neutron, a signature of the double-delta process. Better understanding of multi-nucleon absorption processes probably will require experiments utilizing a detector system which covers the full solid angle and incorporates neutron detection.

The importance of pion-nucleus reactions leading to multi-particle final states and the utility of large-acceptance detector systems at the meson facilities has only recently become apparent. In contrast, 4π-sr detectors have been used from the outset for antiproton physics at LEAR and for relativistic heavy-ion physics, and one is forseen for CEBAF. This is somewhat ironic, since all of these areas of physics must deal with the propagation of pions and deltas in the nucleus. The construction of the BGO ball at LAMPF, described below, was a significant first step toward experiments which can improve our understanding of these very interesting processes. In particular, information about the relative charged-particle multiplicities from pion absorption should soon be forthcoming. The LADS proposal at SIN (Appendix A) would make a further step by incorporating tracking capability, higher neutron detection efficiency, and increased energy range, which are necessary for more detailed studies of the reaction dynamics. Also, the continuous separated pion beams in the πM1 area would allow use of the LADS at much higher intensities than is feasable for a similar detector at LAMPF. This is important, since it is forseen to use the LADS together with an existing external neutron detector. It is also forseen to use the LADS along with either the SUSI spectrometer or a larger-acceptance magnetic spectrometer for studies of pion multiple scattering and double charge exchange, where high beam intensities would also be essential. The LADS should provide important data on these very interesting processes for many years, and we wish to strongly support its construction and research program. The detailed proposals are discussed below.

Current Experiments. Data taking for many of the experiments mentioned above is complete, and some early results have already been published. A description of these experiments and the remaining analysis work is given in our current progress report. Data taking is expected to continue on the proposals, "A Study of the Reaction $^6Li(\pi^+,pp)$ over the $\Delta(1232)$ Resonance Region," NMSU, Maryland, SIN, Arizona State University; G. S. Kyle, NMSU, and P. G. Roos, Maryland, Spokesmen; and "Quasi-Deuteron Absorption on ^6Li and ^{10}B," ASU, Maryland, South Carolina, NMSU; B. G. Ritchie, ASU, Spokesman. These complementary proposals made at LAMPF (No. 948) and SIN (Exp. R-87-05.1) to extend our studies of pion quasi-deuteron absorption to the $^6Li(\pi^+,pp)$ reaction had two basic motivations. First of all, measurements on ^6Li were useful to determine the A dependence of quasi-deuteron absorption. Moreover, the ^6Li nucleus is described rather well in a cluster model as a valence quasi-deuteron and an alpha particle core. Therefore, the energy dependence of the absorption on a loosely-bound quasi-deuteron, possibly affected by the presence of the core nucleons, could be easily compared with that for the tightly-bound core quasi-deuterons, which are more like the absorbing structures in more complex nuclei. These data, together with stopped (π^-,nn) data from SIN,[55] were expected to give a more complete picture of the quasi-deuteron absorption process below and over the $\Delta(1232)$ resonance. Details of the experimental apparatus are contained in our current progress report.

The LAMPF experiment ran for two weeks in December, 1986. Proton coincidence data were obtained for incident energies of T_π = 30, 50, 80, and 115 MeV, taking full advantage of the intense low-energy pion beams available at LEP. These data will be analyzed by a Ph.D. thesis student at ASU. Continued running on ^6Li, and for the first time on ^{10}B, is expected during 1988.

The SIN experiment ran for six weeks in May-June, 1987. A 10-fold increase in acceptance was obtained by using three NaI counters instead of the SUSI spectrometer in coincidence with an array of plastic scintillator telescopes. Thus, a large quantity of proton singles and coincidence data was obtained for incident energies T_π = 115, 140, 165, 190, 220 MeV, both on and off the quasi-free geometries. However, due to significant losses in beam time due to accelerator problems, it may be necessary to finish data taking during 1988. These data will be analyzed by a Ph.D. thesis student at the University of Maryland.

During the SIN run, a limited amount of $^6Li(\pi^-,pp)$ data was also obtained for 165 MeV pions. This reaction must involve all three protons in ^6Li and would be populated via a direct π^-ppp absorption process or via two-step mechanisms. The observation of two distinct peaks in the proton angular correlation was recently reported by a Japanese group.[56] One peak was interpreted as due to a $\pi^-p\rightarrow\pi^0n$ (initial charge exchange) reaction followed by $\pi^0 pp \rightarrow pp$ (absorption on an I=1 nucleon pair), which would largely preserve the quasi-free p-p angular correlation. A second peak was interpreted as an absorption reaction $\pi^- pp \rightarrow pn$ followed by a hard p-p final state scattering, giving an opening angle of about 90^o. The Japanese experiment lacked energy information, which would aid in the interpretation, and their paper gave no detail about particle identification. The SIN experiment has full kinematic information for the two protons, and presumably better rejection of the pion scattering events, which were observed to completely dominate the inclusive (π^-,pp) yield. Should we verify the Japanese results at 165 MeV, our studies of the π^--induced reaction would probably continue.

Another experiment in progress is "Study of π Absorption above/below the Δ(3,3) Resonance Region," LAMPF, NMSU (Kyle), Pennsylvania, Rutgers, Texas; R.D. Ransome, Rutgers, and C.L. Morris, LAMPF, co-Spokesmen. These LAMPF experiments (Nos. 993/994) propose to measure pion absorption on several nuclei from A = 6 to 208 at energies below and over the resonance region using the BGO ball detector. The BGO ball is a very large (greater than 2π sr.) array of ΔE-E telescopes constructed of thin plastic scintillator material bonded to a BGO stopping detector which are read out with a single photomultiplier tube. The ΔE and E information are separated by the difference in response times for plastic scintillator and BGO. The BGO ball design was chosen as a low-cost, first-generation detector of large multiplicity charged-particle states useful for measuring a wide variety of pion- and proton-induced reactions. First measurements of pion absorption were made during December 1986 on the LEP and P^3

channels, but without NMSU participation due to a scheduling conflict with Exp. 948. This experiment will run again in Fall 1987, and NMSU has been invited to participate.

Proposed Experiments. As mentioned above, our future work is expected to involve larger-acceptance detector arrays. Two such proposals have been submitted to the program committee (BVRA) at SIN. The first is "Pion Absorption in Flight and Nucleon Multiplicities," NIKHEF, Maryland, Free University Amsterdam, KFK Karlsruhe, and NMSU (Kyle); Th. S. Bauer, NIKHEF and H. Breuer, Maryland, Spokesmen.

This proposal is based upon studies of pion absorption in ^{16}O which have been performed for low pion energies at NIKHEF using a large-acceptance array (about 4 sr.) of plastic scintillator telescopes. It is proposed to extend those measurements to higher energies and to include measurements on ^{4}He, using the same detector system at SIN. This experiment would have good solid-angle coverage only for 3N phase space, which tends to coplanarity, but would have some advantages over the BGO ball experiment due to better angular information, higher neutron sensitivity, and high beam-rate capabilities. These measurements would determine the breakdown of the total π-^{4}He absorption into 2N, 3N, and 4N phase space over the delta resonance region, which could show signatures of exotic mechanisms. Dynamical information would be in the form of angular correlations near the scattering plane. The experiment (No. R-87-09.1) has been approved by the BVRA and will probably run in Spring 1988.

It should be mentioned here that the NIKHEF array in coincidence with a magnetic spectrometer (such as SUSI) could be used to obtain the first exclusive measurements of quasi-free pion double scattering and double charge exchange reactions, $(\pi^{\pm},\pi^{\pm}2p)$ and $(\pi^{\pm},\pi^{\mp}2p)$, continuing the studies which began with the inclusive measurements on $^{16,18}O$ described above, and probably extending them to include ^{4}He, where interesting structure has been seen in the inclusive data.[57] These reactions, like pion absorption, must involve at least two nucleons, and thus may be sensitive to nucleon correlations. Near the (3,3) resonance, the rescattering mechanism would proceed dominantly via the I=2 Δ-N intermediate state, which would not couple strongly to pion absorption. However, the non-quasi-free mechanism driven by the I=1 Δ-N interaction would modify the (3,3) isospin cross section ratios, as was seen in quasi-free scattering and single charge exchange. Such measurements were mentioned in the initial proposal to construct the BGO ball; however, it unlikely that it can be used with the necessary beam intensities. Should the absorption proposal run as planned, we would expect to submit this proposal later in 1988.

Our longer-term committment is to the "Proposal to Study Multi-Particle Final States in Pion-Nuclear Reactions with a Large Acceptance Detector (LADS)," Basel, Karlsruhe, LANL, Maryland, MIT, NMSU (Burleson, Kyle, one Postdoctoral Associate), SIN, Zagreb; U. Sennhauser, SIN, Spokesman. The physics motivation for the LADS is described above and in Appendix A. The LADS is a second-generation, large-acceptance detector system incorporating most of the required features for detailed dynamical studies of pion-nucleus reactions leading to multiparticle final states, consistent with a reasonable cost. These are,

1. Solid angle coverage $\geq$ 95% of 4π sr,
2. Proton energy acceptance 20 - 250 MeV,

3. Summed proton energy resolution $\leq$ 10 MeV @ 400 MeV,
4. Good neutron detection efficiency for neutron energy $\geq$ 10 MeV,
5. Angular resolution $\leq 5^{o}$ for protons and $\leq 10^{o}$ for neutrons,
6. Tracking of proton trajectories back to the target,
7. Acceptable probability of double hits, 11% for 32 sectors for 4-particle phase space, and
8. Capability to run with $\geq 10^{7}$ π/sec on target.

The design chosen was a cylindrical array of 32 telescopes with ΔE-E1-E2 configuration constructed of plastic scintillator (BC-400), with an inner radius of 30 cm, outer radius of 65 cm, and a total length of 160 cm, closed by 12 end-cap counter telescopes at each end. Plastic scintillator bars, read out with photomultiplier tubes (PMT's) on each end, will give high neutron efficiency with less gamma efficiency than most other scintillator materials. The cylindrical design results in increased stopping thickness at forward angles. Tracking capability will come from two cylindrical multi-wire proportional counters (MWPC's) of the type used for the SINDRUM detector at SIN. The inner radius will be sufficient to identify particles stopping in the ΔE counter by time-of-flight methods. The detector will have high efficiency for neutron tagging, but poor energy resolution due to the short flight path. It is forseen to scan the phase space of one energetic neutron using an external neutron detector set at a distance of about 3 m, which may be done without loss of phase-space coverage. One desirable feature which has not yet been incorporated in the design is identification of gammas, which may be confused with neutrons at higher energies, when missing energy alone is insufficient to exclude a π^{0} in the final state. We are investigating several possibilities for this, including the addition of an outer layer of streamer tubes to detect the gamma conversion products (e^+-e^- pairs). The trigger must be optimized for each experiment, but use of the CES Starburst as a CAMAC preprocessor for the micro-VAX computer will allow trigger rates up to about 1.5K/sec.

The LADS proposal (R-87-13.1) was approved by the program committee of SIN (BVRA) in June, 1987. Design work will proceed during 1987, construction is planned for 1988 (when the bulk of the funds are required), testing during early 1989, and first data taking starting in Spring, 1989. The experimental program will begin with studies of pion absorption in ^{3,4}He, ^{6,7}Li, ^{12}C, ^{58}Ni, and ^{208}Pb.

The detector system, consisting of 144 plastic scintillator counters read out by 152 5" PMT's and 112 2" PMT's and two cylindrical MWPC's, at an estimated cost of $600K plus machine shop work, represents a substantial construction project. While SIN will bear the greatest portion of the cost, the user groups are expected to contribute the bulk of the manpower and to share in the construction costs. The NMSU group has been asked to take responsibility for construction and partial instrumentation of the end-cap detector telescopes, which would consist of 24 E-blocks read out by a single 5" PMT (XP2041 or equivalent), 24 ΔE-counters read out at each end by 2" PMT's (EMI9813 or equivalent), and sufficient CAMAC electronics for about half of the end-cap system, at a total cost of about $100K, spread over 1988-89. The proposed cost breakdown is given in the attached budget. It is also requested that NMSU hire an additional Postdoctoral Associate to be based at SIN, who would participate our ongoing program there and work on the LADS project.

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