OVERVIEW OF NEW EXPERIMENTAL RESULTS IN MESON-NUCLEUS INTERACTIONS AND FUTURE OPPORTUNITIES*

R.J. PETERSON

Nuclear Physics Laboratory, University of Colorado
Boulder Colorado, 80309-0446 USA

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Progress in meson–nucleus interactions is sketched, including meson production, absorption, and scattering. Extensions to eta meson interactions are becoming very important as extensions to the large body of pi meson data, and several new experiments with positive K mesons have been completed. π meson reactions themselves have been extended to higher energies, to more complete coverage of the reaction products, and in production, to energies strikingly near threshold.

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1. π-nucleus scattering

Elastic and inelastic scattering of pions was the first of the reactions studied with mesons on complex nuclei, and much has been settled. At this Conference no results with resonant-energy pions were even shown, since the mechanisms are so well known. Instead, efforts focussed on lower and higher beam energies, with one of the principal features being the deeper nuclear penetration.

Figure 1 shows reaction cross sections, per nucleon, measured at 50 MeV on $T = 0$ targets in two TRIUMF experiments [1, 2]. The constant value indicates a great deal of transparency to these pions, also reproduced by the optical model results shown. Friedman showed similar data in a different format, as a function of energy. Low energy elastic scattering on many targets is shown in Fig. 2, with the optical model in good agreement except for targets with a large neutron excess [3]. If the discrepancy comes from the

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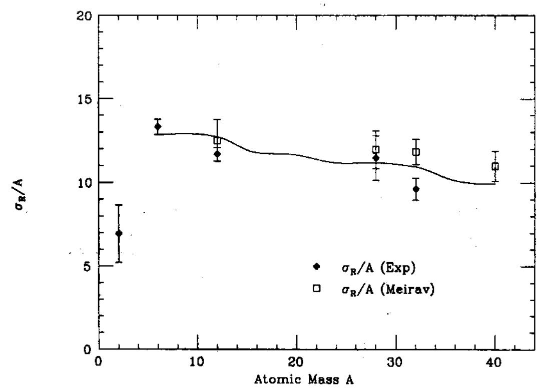

Fig. 1. Measured reaction cross sections for 50 MeV π^+ on $T = 0$ targets are compared to 'standard' optical model predictions [1]. These preliminary new data agree with points from [2], shown as squares.

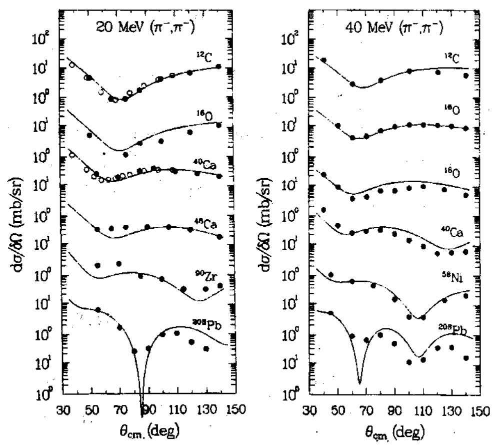

Fig. 2. Solid data points for π^- elastic scattering [3] and earlier data are compared to optical model calculations using the MSU model. The parameters give good agreement with the data for light nuclei, but fail for heavy targets.

poorly-determined isovector potential, data for pion charge exchange to isobaric analog states in heavy nuclei should fix this problem. An experiment planned at LAMPF in 1993 aims to do this. Optical model methods for low energy pions have become very sophisticated, but are perhaps overly-rich in parameters.

Neutral π production in heavy ion reactions also shows evidence of long mean free paths for the pion [4], but a comprehensive comparison of the internal propagation of low energy pions from a variety of reactions is not yet available.

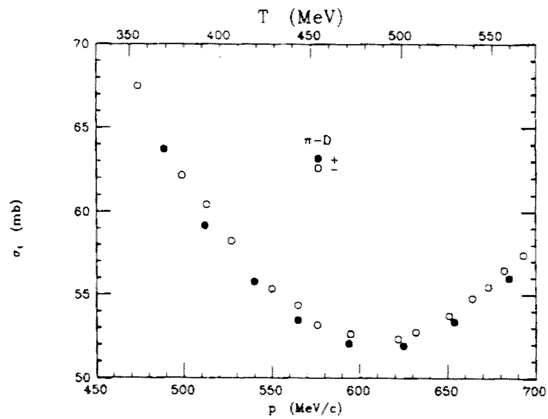

Fig. 3. Measured total cross sections of pions on deuterium show a minimum near 500 MeV [5], where much of the effort at LAMPF has concentrated.

Above the resonance the pion mean free path again increases, with a distinct minimum in the π-D total cross sections at 500 MeV [5], as shown in Fig. 3. This is just the energy where so much effort has been carried out at LAMPF, as shown by Morris. Single charge exchange has also been carried out at 500 MeV [6], and new elastic data will be shown below. Even double charge exchange seems easier to interpret at higher pion energies.

The other feature that becomes simple at high pion energies is that the short wavelength permits incoherent or quasifree scattering, as shown by Morris. For momentum transfers beyond twice the Fermi momentum, we measure an effective number of nucleons available to single quasifree scattering. This corresponds to scattering from nuclear densities beyond some radius or density, using

$$A_{\text{eff}} = 4\pi \int_R^\infty \rho(r) r^2 dr\,,$$

and then evaluating $\rho(R)/\rho(r=0)$.

Recent data at 500 MeV for (π^-, π°) SCX [7] and both π^+ and π^- noncharge exchange (NCX) [8] quasifree scattering give the densities reached for a range of nuclei shown in Fig. 4, showing that at this energy pions react at about one fifth of the central nuclear density. Also shown in Fig. 4 are very recent results from 720 MeV/c k$^+$ quasielastic scattering [9], showing that this least-strongly-interacting hadron probe reaches about twice the density reached by the 500 MeV pions.

Quasielastic pion scattering may be compared to the same sort of nuclear response calculation familiar for electron scattering, but differently

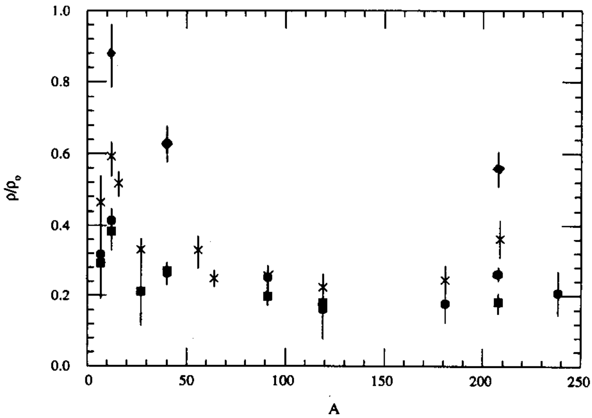

Fig. 4. Quasifree SCX and NCX scattering of 500 MeV pions on many nuclei gives inclusive singly-differential cross sections proportional to the number of nucleons seen by the scattering. These numbers correspond to the volume of the sample beyond some radius. Here are shown the densities relative to that at r=0 at that radius reached. Data are for SCX (crosses), π^+ NCX (squares), and π^- NCX (circles) [7, 8]. Diamonds show the results for 720 MeV/c K$^+$ quasielastic scattering [9], reaching about twice the density seen by the pions.

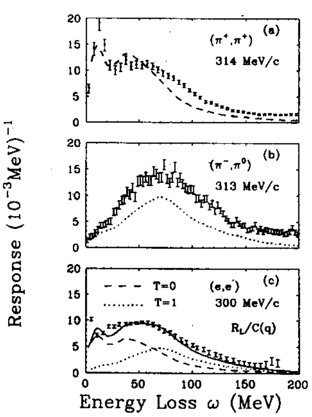

Fig. 5. Responses of carbon, the ratios of doubly differential cross sections to the free cross sections and the number of nucleons, are compared for 500 MeV pion NCX and SCX [7] and electron scattering near q=300 MeV/c. Theory for the $T = 0$ and $T = 1$ responses are added for the charge scattering [10], but separated for the pion scattering. The expected isoscalar enhancement and softening are seen at this momentum transfer.

sensitive to the isospin. Figure 5 [7] shows data for pion SCX, compared to the isovector response of [10], with NCX data compared to the isoscalar response. The great differences seen in the two responses are summed for

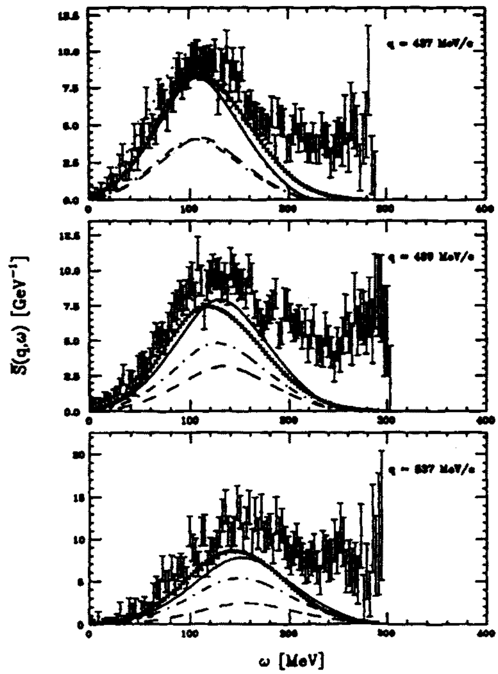

Fig. 6. Pion SCX responses near q=500 MeV/c are compared to $S = 0$ (dashed) and $S = 1$ (dotdashed) RPA calculations, and the solid line as their sum. The heavy curve is the result of fitting the QE peak above a background, for better comparison to the theory [11]. In contrast to the data near 300 MeV/c, these results show a largely uncorrelated response.

the response to electron scattering, also shown. Isoscalar interactions are important at these momentum transfers near 300 MeV/c, and their effects are separately available with pion reactions. At larger momentum transfers, these interactions die out, leaving uncorrelated QF scattering. Figure 6 [11] shows 500 MeV pion SCX compared to the $S = 0$ and $S = 1$ isovector responses computed within the RPA. These data near $q = 500$ MeV/c show the uncorrelated response expected.

There is a rich future for these uses of mesons for quasielastic scattering, using their simple natures, fairly long nuclear penetrations, and the wide range of spin and isospin sensitivities available.

2. Deltas in nuclei

Reaction models that include the explicit role of Δ's in nuclei are used at resonance pion energies, where the short mean free path makes all models seem adequate. The most striking evidence for a Δ response in a complex

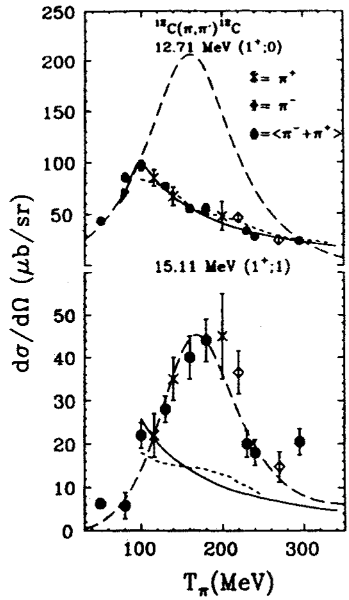

Fig. 7. Cross sections for π inelastic scattering to the 1^+ states of ^{12}C are shown at q=120 MeV/c, atop the diffraction peak. The solid line is proportional to $\sin^2\theta$, while the short-dashed curve is a DWIA calculation, which agrees with the $T = 0$ data. The long-dashed curve is proportional to the free π-nucleon differential cross section at this q for the proper S, T channel, and matches the $T = 1$ data [12].

nucleus is the excitation function for the two 1^+ states of ^{12}C shown in Fig. 8 [12]. The T=0 state responds as predicted by the DWIA, as a *nuclear* excitation. The T=1 state responds instead as a free *nucleon* excitation. Although the quantum numbers of the 15.1 MeV excitation are the same as those for exciting a nucleon to a Δ, there is no other reason to expect this similarity. The Δ-hole model, even with carefully chosen Δ-nucleus parameters, does not account for this striking effect [13]. A new pion SCX experiment at LAMPF will observe the same transition without the isoscalar background, using the Neutral Meson Spectrometer to achieve the high resolution needed.

A Δ in a nuclear ground state would permit direct QF pion double charge exchange. This can be distinguished by the (π^+, π^- p) exclusive reaction, as shown by Morris. The cascade model that accounts for the exclusive NCX data also predicts the DCX. The data are a factor of ten above this, which could be interpreted as due to a 1% Δ component of the nuclear ground state. It is possible to do a much better experiment, as proposed for LAMPF [14].

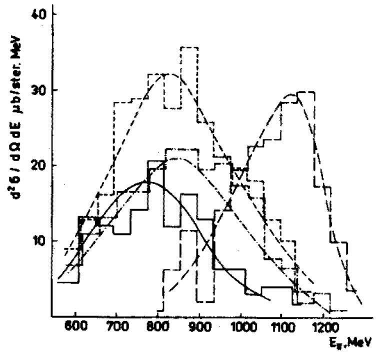

Fig. 8. Pion SCX at 1100 MeV/c and 10° on several targets shows a very strong direct excitation of the Δ, near 800 MeV π^0 energy [17]. Dashed lines for $\pi^- p \rightarrow \pi^0_n$; full lines $\pi^+ p \rightarrow \pi^0 \Delta^{++} (x2)$; dotted π^-Al; dot-dash π^- on C.

Direct population of Δ's in nuclei is popular with high energy electron and proton reactions, as well as with a variety of heavier projectiles. Even LAMPF energies are not high enough to make this excitation evident with pion beams, although indirect evidence [15, 16] says the process is important for large energy losses with 500 MeV beams. A tantalizing example of a strong Δ peak in higher energy pion SCX comes from Dubna, and is shown as Fig. 8 [17]. A new detector is nearing completion to allow better study of this mode with pions, to be compared as an isovector, transverse spin-flip reaction to data available by electron scattering exciting the Δ within nuclei.

A long-standing question has been the attractive coherence of states formed with real pions in a nucleus, in the spin longitudinal $(\sigma \cdot q)$ channel. Using the (^{3}He,t) reaction to generate pions in carbon through a delta excitation, Rousteau reported on the Saturne studies of the single-pion decay using a large solid angle detector. The nuclear missing mass in this channel was found to be low, as the nucleus responded coherently to propagate the pion, which also maintained the direction in which it was produced. These results confirm the expectation of a pion field in a nucleus. Another experiment to measure the effects of the nuclear pion field is by the 500 MeV $(\vec{p}, \vec{n})$ reaction, carried out at LAMPF [18]. Here, no collective enhancement due to the longitudinal pion field was observed at $q = 1.7$ fm^{-1}. Oltmanns considered the theory of the proton reaction at 800 MeV, without the invaluable spin observables. Gilman presented a design for a future LAMPF experiment, using the (p, n) reaction in place of (^{3}He,t) and again detecting a single decay pion. One difference between the (p, n) and (^{3}He,t) reactions is the different nuclear densities reached by the beams. In any case, we do not yet have a consistent picture of the role of pion fields in complex nuclei.

3. Absorption and production of pions

Pions can be absorbed by one, two, or more nucleons in a target. On one nucleon the absorption needs the highest momentum components of the nucleon wave function, and cross sections are small. The most likely absorption of a pion on just two nucleons has been pursued to very low pion energies for deuterium [19], but becomes lost in heavy nuclei, where more nucleons share the process. Large solid angle detectors show evidence of multinucleon absorption on light nuclei [20], while many nucleons share the process in heavy nuclei [21]. The limit of this counting comes to fission, where the pion charge, high energy, and low momentum are distributed among all nucleons, since fission is the slowest and last nuclear reaction to occur. Figure 9 [22] shows fission probabilities for pions from 80 to 140 MeV plotted against the fissility of the system including the charge. For light nuclei, these are far above the data for stopped π^- [23], and scanty data at higher pion energies do not raise the probabilities much. We seem to have reached a maximum nuclear excitation of about 200 MeV, such that any more does not leave enough nucleus to fission.

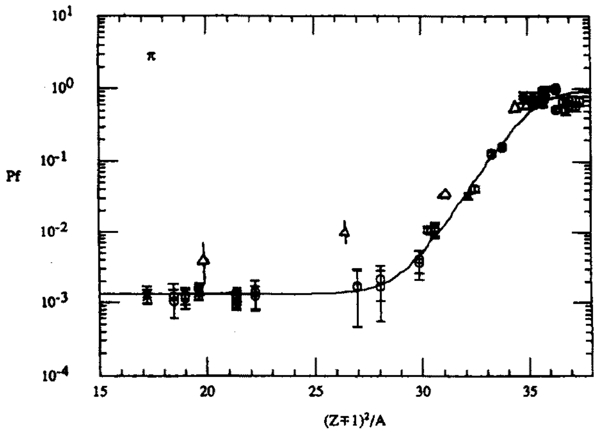

Fig. 9. Fission probabilities for many targets are plotted for π^+ and π^- from 80 to 140 MeV, showing a smooth dependence on the fissility including the pion charge. The curve is a guide to the eye. Triangular points show the $\bar{p}$ fission probabilities shown by von Egidy, with only a small increase in P_f for the much higher energy available in the annihilation.

Nuclear absorption of stopped $\bar{p}$ was shown by von Egidy to release an average of 5 pions, with an initial energy available of nearly 2 GeV. Nonetheless, fission probabilities from $\bar{p}$ do not increase much above those observed for the pions, as shown by the triangular points in Fig. 9.

The situation between absorption on one or two and on many nucleons is being addressed with the high-solid angle detector LADS at PSI. A careful program beginning with light nuclei is being carried out. Our colleagues in heavy ion physics are able to learn a lot about their reaction mechanisms by measuring the spectra of heavy fragments, where the charges and binding energies of the fragments determine their exit probabilities from the system of interest. One application of a common heavy ion reaction model to products of pion reactions found good agreement, but the data for comparison were only for helium isotopes [24]. We need a careful measurement with detectors as sophisticated as those used for heavy ion reactions and antiprotons to explore the outgoing products from pion reactions to learn how to use this valuable signature.

Pions may also be produced within a complex nucleus. When generated by a heavy ion reaction, the debris gives evidence of the same long mean free path familiar with free beams [4]. Photopion reactions seem fairly well understood, and new experimental facilities will push this much farther. When pions are produced by pions, however, a new effect seems to be seen. At large energy loss the pions, both produced and original, have energies near the Δ and should be quickly lost, producing a dip in the spectrum near 180 MeV. As shown by Morris, this is not the case. One story would be that the two pions form a temporary σ meson, which has a weak coupling and a long mean free path in nuclei. The clear way to test this idea is by comparisons to photopion spectra and to pion inclusive spectra with large energy losses but starting with higher pion energies to move the Δ self-absorption. At this conference Mashnik showed inclusive pion spectra following bombardment by 1.5 and 3 GeV/c pions. Again, no dip due to self-absorption is noted near 180 MeV.

The recent emphasis on pion production measurements is towards threshold. Pocanic showed $(\pi, 2\pi)$ data from LAMPF for the least well understood channel, with π^+ and π° in the final state. The data are strongly related to questions of chiral symmetry and the $\pi - \pi$ scattering length.

Proton-induced pion production was shown by Meyer, extended to a D target. He found the nuclear effects to be strikingly important, but of a trivial origin. Detailed agreement with the exquisite data will surely give new information. Schuberth discussed his new pion production experiment on Celsius, which allowed him to get yet nearer threshold than the IUCF data. The high-quality beams and sensitive detectors now operating for these coolers are proving very effective, and certainly lead to high expectations with COSY.

Proton-induced pion production on the deuteron has been taken very near to threshold [25], using polarized beam for new sensitivities. A strong p-wave channel, seen by the interference in the spin amplitudes, persists down to very low energies, not as found for pion production on free nucleons. It would certainly be valuable to add spin observables to the other cooler facilities.

4. Heavier mesons

Production and reactions of heavier mesons can be expected to follow our understandings of pion reactions. The most familiar examples are in hypernuclei, both by the low-q (K,π) reactions and by the high-q (π,K) reactions leading to Λ hypernuclei. New facilities have been designed, but not funded, that would permit sufficient resolution to measure the full spectroscopy of Λ hypernuclei. Figure 10 shows a current spectrum compared to what is possible in the future.

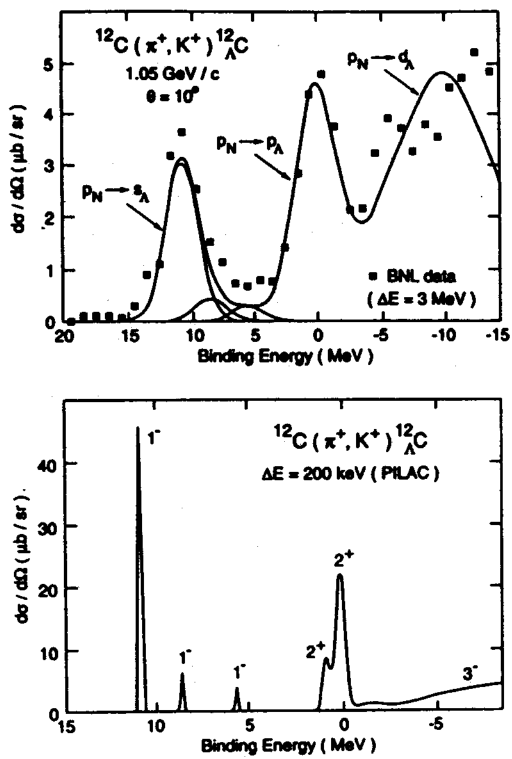

Fig. 10. At the top, the measured excitation spectrum at θ=10° is shown for the $^{12}C(\pi^+,K^+)^{12}_{\lambda}C$ reaction at a pion lab momentum of 1.05 GeV/c. The experimental energy resolution is $\Delta E = 3$ MeV. The solid curves are DWBA calculations using π^+ and K^+ optical potentials fitted to elastic scattering. At the bottom, the theoretical spectrum is given for $\Delta E = 200$ keV. The fine structure of the 1^- and 2^+ states can now be resolved [26].

Since the K^+ has a fairly long mean free path in nuclei, it is attractive to look for medium modifications of the K^+-nucleon interaction within nuclei. This is commonly called 'swollen nucleons'. Friedman showed K^+-nuclear total cross sections, some of which are published [27]. The ratio of C to D cross sections is greater than 6, which is above what is predicted by conventional nuclear effects. Before this can receive too much emphasis, we must consider how well we know the elementary K^+-nucleon cross sections. Figure 11 shows that in the $T = 0$ channel (related to K^+-neutron), the experimental situation is not yet settled. A recent study of K^+ quasielastic scattering and a new measurement of K^+ nuclear elastic scattering, with a careful absolute normalization, will clarify this greatly.

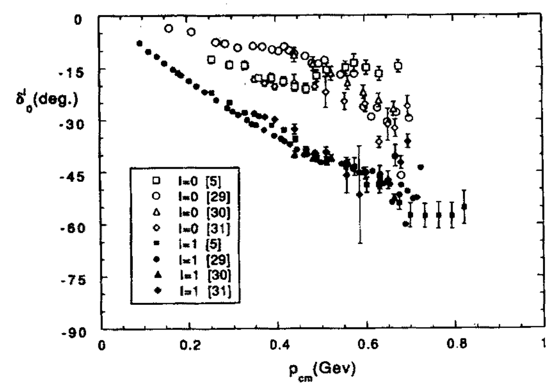

Fig. 11. Recent data for K^+ -nucleon S-wave phase shifts seem to determine the T=1 value very well, but the T=0 channel is still ambiguous [28].

A large number of speakers were enthusiastic about η mesons, attracted by their simple quantum numbers and the possible complexities of their structure and decays. Modern detectors also now make it cheap to measure η's, without a large magnetic spectrometer. These mesons can also serve as triggers to isolate particular baryon resonances, especially the S_{11}, as shown by Schoch. A next step would be to locate the S_{11} by η production on a complex target, to examine the interactions and propagation of this 'giant dipole nucleon' in a nuclear environment.

Recoil particle detection in the $p + d \rightarrow {}^3\text{He}+\eta$ reaction, developed at Saturne, is a very efficient means to learn about η production. Encouraged by the spectacular successes of Celsius and IUCF pion production near threshold, Machner and Roderburg showed how COSY could extend these studies to η mesons. Yet heavier meson production will also be available at COSY, and it is exciting to consider how comparisons of a range of meson mechanisms near threshold could lead to great insights.

Direct, coherent (π, η) reactions to discrete states have begun at LAMPF, and, as shown by Liu, can give information on η-nucleon and η-nucleus interactions. The momentum transfer is large, but a model carried only to second-order seems sufficient to describe the data. A new detector at LAMPF will be able to improve these data greatly.

5. Higher pion energies

Much of the reaction mechanism used for π-nucleus scattering so far comes from the Δ resonance, but at some sufficiently high beam energy it is simpler to treat 'direct' reactions, where the resonances overlap. Figure 12 compares measured total cross sections of π^+ and π^- (averaged) on C [29] to the average on H (times 7). The resonances visible in the free case are smoothed together in C, permitting a direct reaction picture beyond about 400 MeV.

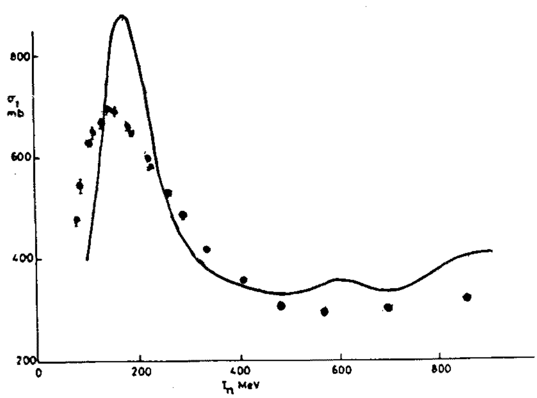

Fig. 12. The average of measured total cross sections of π^+ and π^- on C [29] is compared to the average on H, multiplied by 7. The higher resonances visible in the elementary reaction are blurred for C, showing that above 400 MeV π-nucleus reactions can be treated as direct, not resonant, processes.

This has been used in a recent reformulation of the π-nucleus optical model [30]. The 'old' way used the code ROMPIN and the partial wave decomposition of the π-N scattering, with very large matrices and long running times for heavy nuclei. The 'new' way, compared to ROMPIN and the data for Ca in Fig. 13 is instead based on a direct eikonal model. The results of the two methods agree in value and accuracy, but with a tremendous saving in computer time with the eikonal method. We need no longer fear the computations needed for high energy pion reactions. An extensive body of new data has been obtained at KEK [31], scattering π^- from C at beam momenta from 640 to 1000 MeV/c. With better than 2

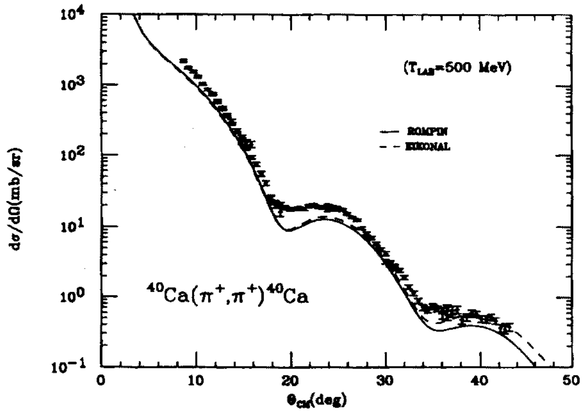

Fig. 13. Recent data from LAMPF for 500 MeV π^+ elastically scattered from Ca are compared to two optical model curves [30]. The 'Rompin' curve uses the multipoles of the π-nucleon interaction, as familiar in the Δ region, and is very expensive to run. A new formulation suited to high energy pions is based on the eikonal model, and gives much the same accuracy and results at a small fraction of the computing time. Very similar agreements are found for π^- data.

MeV resolution, the standard levels of ^{12}C are well-resolved, and the pion-nucleus optical potential can be greatly extended in energy.

We can consider the scattering of high energy pions from nuclei as similar to electron scattering, but with different couplings to nuclear spin and isospin. Figure 14 shows an example of these couplings at 1500 MeV. Inelastic scattering will largely couple to $S = T = 0$ until very large momentum transfers, while SCX will explore $T = 1$ modes, with $S = 0$ or 1 depending on q. The spin zero pion must couple to spin excitations by the transverse $(\sigma \times q)$ mode.

Quasielastic scattering near 400 MeV/c is going to be largely coupled to $T = 0$ modes, again without spin, for NCX, but for SCX the coupling will be to $T = S = 1$ modes. These curves are at a fixed π-nucleon energy, and should be averaged over quite a large energy range before being applied to a nucleus.

As an example of what one might see in high energy pion QE scattering, Fig. 15 shows electron, kaon, and pion inclusive data, at a range of angles and energies, replotted to the format of y-scaling [33]. If the conditions of y-scaling are met, a single curve will represent all these points, as most familiar for electron scattering [34]. This seems to be the case for the meson data shown, but we clearly need better statistical accuracy in the important region of large negative y. The curves are the electron scattering response calculations of [10], scaled by the effective number of nucleons for the meson data. These experiments, including SCX, will become more sensitive and

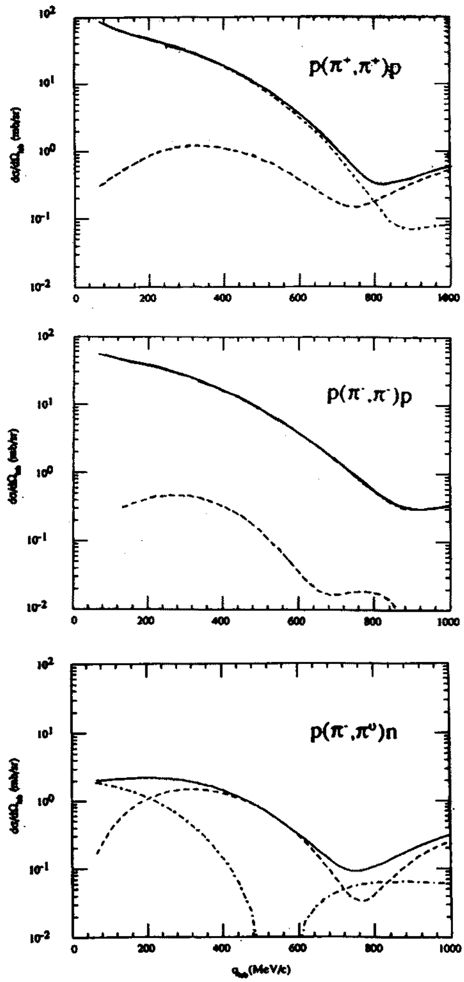

Fig. 14. Free π-nucleon scattering cross sections at 1500 MeV are shown for spin (dashed), nonspin (dot-dashed), and summed scattering [32]. These are the driving terms for π-nucleus reactions at this energy.

accurate with higher pion beam energies.

6. Opportunities

The easy experiments with pion beams have now mostly been done, with the greatest effort on inclusive (single-arm) scattering or detection of, at most, two reaction products. So long as the final nuclear state is determined by data of high resolution, these can be complete results for a limited class of processes. The next step in the evolution of experiments

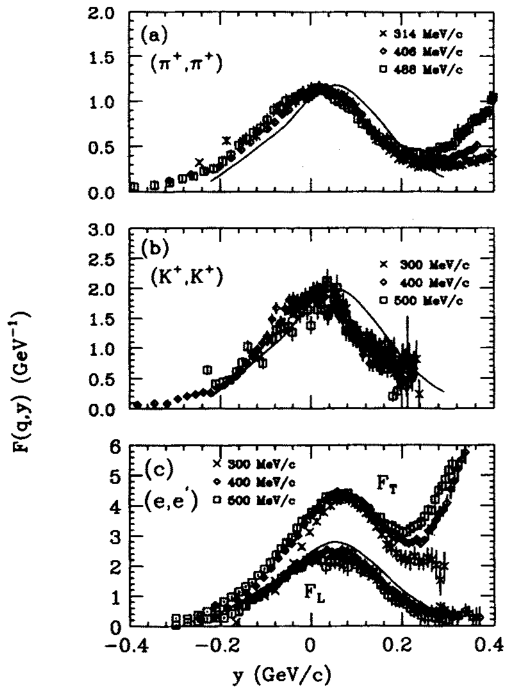

Fig. 15. Data for 500 MeV π^+, 720 MeV/c K^+ and electron (both charge and transverse) scattering are plotted for several momentum transfers as functions of y, the momentum of the struck nucleon along the q direction [8]. Free scattering would give a sharp peak at y=0, and a Fermi gas gives QE scattering as a parabola out to $\pm k_f$. Lines are the RPA charge theory of [10].

with π beams must be towards more complete coverage of the variety and full phase space of the reaction products. More than is the case for any other projectile, the pion calls for full coverage, since as a field the projectile can couple to so many nuclear processes.

Pions produced, and possibly reabsorbed, in many high energy nuclear reactions are also important members of a chain of reaction mechanisms. Once we know the π-nucleus interaction well enough, we can begin to use the pions for insights into further reaction details. Someone needs to think a lot to see if we now have enough information and wisdom on the π-nucleus systematics to allow this, and to suggest the missing experimental studies. As ηs, kaons, and other heavy mesons are also produced by many reactions as the beam energies continue to increase, we also need to extend our understanding of the more general relations of mesons in nuclear reactions.

Are there surprises waiting in pion-nucleus physics? We saw at this Conference the suggestion of a dibaryon selected by pion DCX, as shown by Wagner. There are also suggestions of an anomaly in (p,π) spectra that could also be a narrow dibaryon resonance [35], but the evidence seems to come and go. The σ effect suggested by Morris to explain the shapes of pion spectra at large energy loss also would be novel, and could be checked readily by comparison to the right complementary experiments. Pion absorption experiments, raising the beam energy to increase nuclear excitations with little angular momentum, could provide enough excitation to induce the 'multifragmentation' phase change so sought after with heavy ion beams. Some appropriate signature of this process needs to be established. The work remaining to be carried out with pion beams and pion reaction products has some obvious goals and anticipated results, but there is also a great need for new wisdom in the directions we know less about.

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