PION PRODUCTION IN NUCLEUS-NUCLEUS COLLISIONS*

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ABSTRACT

Current work on pion production in high-energy nucleus-nucleus collisions is reviewed. The majority of existing data are of the inclusive variety in which a single final state pion is detected. Experimental data are compared and their possible contributions to obtaining new information on nuclear structure is discussed. Various models which attempt to explain the observed single-inclusive-pion spectra either on the basis of a nucleon-nucleus interaction in which Fermi motion is included or on some type of cooperative model are examined. Other areas of interest involving pion production include tests of charge symmetry and pion multiplicities.

INTRODUCTION

In the last few years it has become possible to study high-energy nucleus-nucleus interactions at several laboratories throughout the world (Berkeley, Dubna, Princeton-Penn, and Saclay). Beams of nuclei with kinetic energies ranging from several hundred to several GeV/nucleon have been employed in a variety of studies. Although the number of experiments on pion production is relatively small, it is worthwhile reviewing the existing data in order to understand the motivation for these experiments and to determine what has been learned from these early measurements. Where appropriate, comparisons between experiments will be made. This review will be restricted to the study of the production of pions with kinetic energies $\gtrsim$ 100 MeV. Finally, I will discuss possible future directions for experiments involving pion production.

SINGLE-PARTICLE INCLUSIVE EXPERIMENTS

The majority of the data that will be discussed involve experiments in which a single charged pion in the final state is measured, these are referred to as single-particle inclusive measurements:

$$A + B \rightarrow \pi^{\pm} + X, \tag{1}$$

where A is the incident heavy-ion, B the nuclear target, and X represents everything that *is not measured* in the experiment. Table I lists the experiments[1-4] that will be discussed. All of these experiments employed conventional counter techniques for particle detection and identification. A majority of this review will be concerned with recent results obtained at Berkeley.[1]

The experiments on high-energy pion production in nucleus-nucleus collisions have typically been motivated by the same question. To which extent are very energetic pions, that is, pions with energies considerably larger than those which result from simple nucleon-nucleus collisions, produced in the collisions of deuteron, alpha and heavier beams with nuclei? Could such high energy pions be explained in terms of nu-

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TABLE I: EXPERIMENTS ON PION PRODUCTION

	Experiments	Energies
Ref. 1 (Berkeley)	(p, d, α, C) + A → $\pi^{\pm}$ + X (2.5° Lab) ↳(variety of targets)	p (1.05 - 4.8 GeV) d,α (1.05 and 2.1 GeV/nucleon) C (1.05 GeV/nucleon)
Ref. 2 (Dubna)	d + Cu → π^- + X (0° Lab)	d (7.6 - 8.5 GeV)
Ref. 3 (PPA)	^{14}N + A → π^- + X (3° and 15° Lab) ^{14}N + A → π^+ + X (15° Lab) ↳(variety of targets)	^{14}N (520 MeV/nucleon) ^{14}N (520 MeV/nucleon)
Ref. 4 (Saclay)	d + A → $\pi^{\pm}$ + X (15.4° Lab) ↳(variety of targets)	d (1.16 and 1.62 GeV)

cleon-nucleon processes in which Fermi motion is included in both projectile and target, or are more complicated processes required? In addition, such data can be used to test whether high energy ideas such as scaling[5] can be applied to pion production resulting from nuclear collisions.

The Berkeley experiment[1] has measured the single pion inclusive spectra produced by high energy proton, deuteron, alpha, and carbon beams interacting with a variety of targets (Be, C, Cu, Pb). Figure 1 shows the results of π^- production by protons of various energies on a carbon target. The spectra are observed to fall rapidly at higher pion momenta. The sharp cut-off in each spectrum is a result of energy and momentum conservation and corresponds to the proton transferring almost all of its kinetic energy to the creation of a pion. A remarkable feature of these data is observed when the invariant cross section E/k^2 $(d^2\sigma/d\Omega\, dk)$ is plotted against the scaling parameter,

$x' = \dfrac{(k^*_{\parallel})}{(k^*_{\parallel})_{max}}$ as shown in Fig. 2a. All of the data are seen to lie on a universal curve, suggesting that negative inclusive pion spectra scale even at 1 GeV, a somewhat unexpected result. A similar feature is observed for each of the target nuclei used. This scaling behavior, where the pion yield does not depend on the energy but only on the scaling variable x' (at fixed $k_\perp$) is familiar in very high energy elementary particle processes. It should be kept in mind that since this experiment was performed at a fixed lab angle of 2.5°, $k_\perp$ is not quite constant. This effect is most important near $x' = 1$ where it could change the results by as much as a factor of 2. Fig. 2 (b) shows the invariant cross section for producing negative pions by 1.05 and 2.1 GeV/nucleon deuteron and alpha projectiles on a carbon target. Again the scaling feature is reasonably satisfied. Notice that the fall off in x' increases as the mass of the incident projectile increases. This suggests that relatively loosely bound objects, like nuclei, do not transfer a large fraction of their kinetic energy to creating individual pions. For the case of π^- production by deuterons, these results differ from those of the Dubna[2] group who find that the ratio:

$$R(x') = \frac{\sigma(d + Cu \rightarrow \pi^- + X)}{\sigma(p + Cu \rightarrow \pi^- + X)}$$

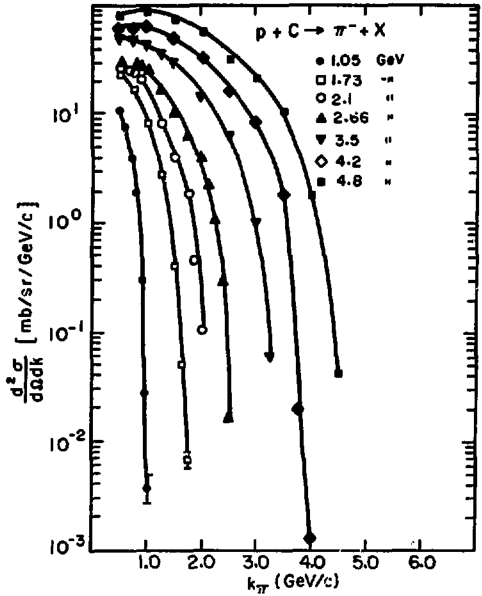

Fig. 1: Cross section for negative pion production (Ref. 1) at 2.5° (lab) by protons (1.05-4.2 (GeV)) from a carbon target vs. the pion momentum (k_π).

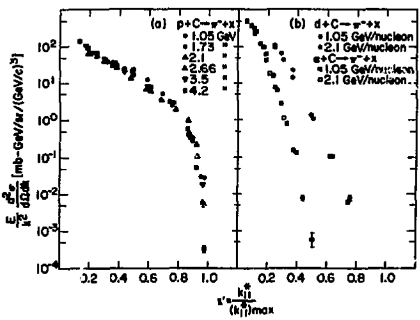

Fig. 2: Invariant cross section (Ref. 1) for negative pion production at 2.5° (lab), (a) incident protons (1.05-4.2 GeV), (b) incident deuterons and alphas (1.05 and 2.1 GeV/nucleon).

at the same kinetic energy is independent of x′ in the interval $0.6 \lesssim x' \lesssim 1.0$. The Dubna data is shown in Fig. 3. It is unlikely that the *different kinematical conditions* of these two experiments can account for this discrepancy.

Negative pion production cross-sections[1] for 2.1 GeV/nucleon protons, deuterons, and alphas incident on a carbon target are shown in Fig. 4. The following features are evident: (1) The heavier the projectile, the larger the cross-section (at 1 GeV/c this ratio is ∿ 10:5:1), (2) The maximum energy of observed pions increases as the mass of the projectile increases. The larger production cross sections for deuterons and alphas compared to protons is attributed to the presence of neutrons which produce π^-'s more abundantly than do protons.

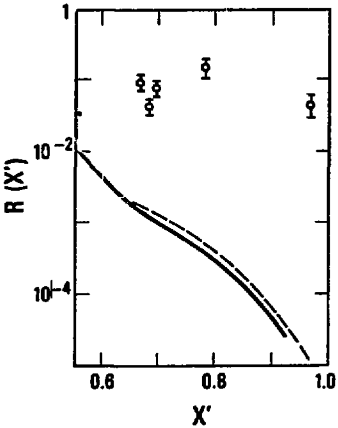

Fig. 3: Data of Ref. 2. Ratio (R(x′)) of deuteron and proton pion production cross sections (at same total kinetic energy) vs. the scaling variable x′. Data taken on Cu target.

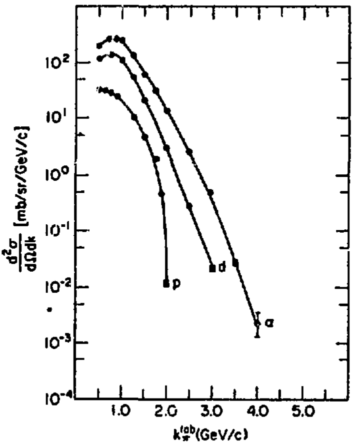

Fig. 4: Laboratory cross section ($d^2\sigma/d\Omega dk$) for negative pion production (Ref. 1) at 2.5° (lab) for 2.1 GeV/n p,d,α on carbon target.

It is of considerable interest to ascertain whether these high-energy pions are produced in interactions in which several nucleons inside of the projectile nucleus participate in a cooperative fashion, or whether a single nucleon-nucleus collision with the inclusion of Fermi motion in both the projectile and target is sufficient to explain the observed spectra. Fig. 5a shows the results of a calculation by the Berkeley group[1] based on a model in which all pions are produced in individual nucleon-nucleus collisions with Fermi motion included. The predictions of the model are compared with the 1.05 and 2.1 GeV/nucleon deuteron data taken with a carbon target. The general behavior of the measured cross-sections for fast pions is reproduced quite well. There were no free parameters involved in the calculation. These results disagree with the conclusions of the Dubna group[2,6] who claim to be unable to fit their data with a similar model. The results of their calculation are shown in Fig. 3 (solid and dashed curves).

The model used by the Berkeley group has also been applied to negative pions produced by 1.05 and 2.1 GeV/nucleon incident alpha particles. The comparison between the data and the model is shown in Fig. 5b. Although the general trend of the data is followed, quantitatively the agreement between the two is poor. This could be due to a breakdown of the model, or to a poor choice for the single-nucleon momentum distribution, which for the alpha is not well known. Indeed, one of the interesting possibilities associated with pion production measurements will be the possibility of extracting information concerning nucleon-momentum distributions, and in particular the high momentum components of such distributions.

Further insight into the production mechanism for pions can be obtained by studying the dependence of the production cross section on the target mass. The Berkeley results[1] have been parameterized in the form: $\sigma \propto A^n$, where A is the mass of the target. A plot of n as a function of pion momentum for 2.1 GeV/nucleon alphas is shown in

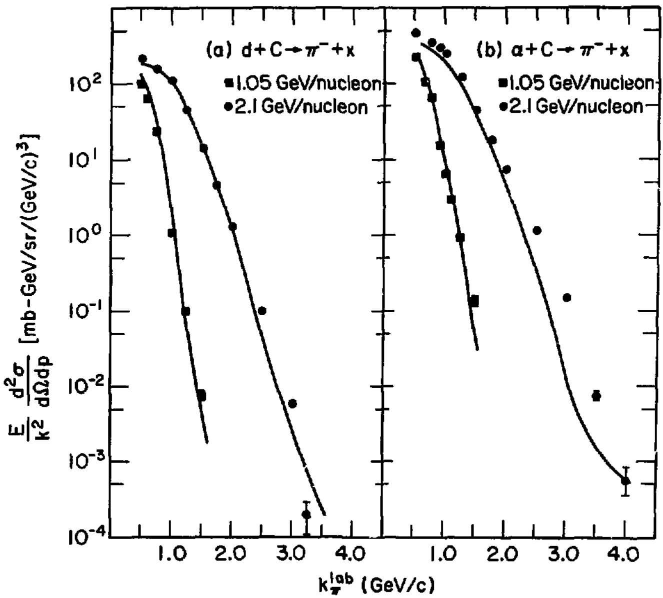

Fig. 5: Invariant cross section for negative-pion production at 2.5° (lab) by 1.05 and 2.1 GeV/n (a) deuteron and (b) alpha beams. The solid line represents the prediction of model described in Ref. 1.

Fig. 6. For high momentum ($\gtrsim$ 1 GeV/c) the dependence of $A^{1/3}$ suggests peripheral production. For lower-momentum pions, the dependence is more pronounced, suggesting that slow pions are produced in more central collisions. A similar effect is seen at the lower energy (1.05 GeV/nucleon) and in the deuteron data.[1]

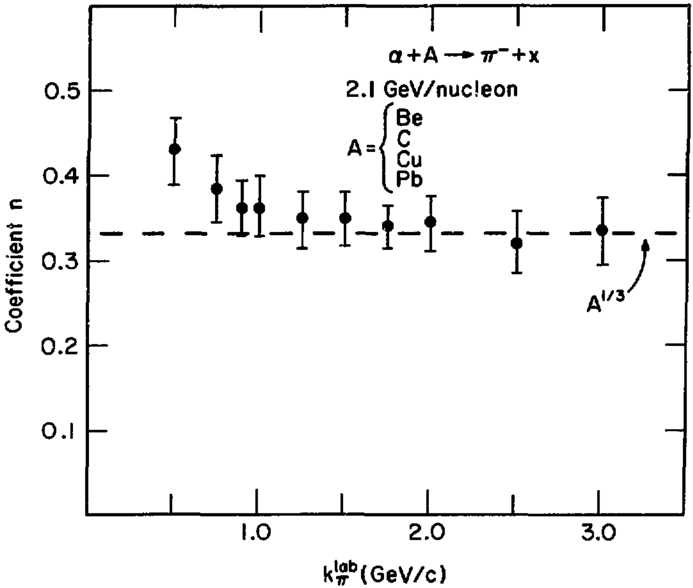

Fig. 6: Dependence of the pion production on A. Ref. (1) has assumed a form: $\sigma \propto A^n$, where A = target mass.

Up to this point we have emphasized pion production by very light nuclei (p,d, and α beams). The PPA experiment[3] has measured pion production by 520 MeV/nucleon ^{14}N ions at 3° and 15° in the laboratory, with pion kinetic energies in the range of 100-700 MeV. Figure 7a shows the dependence of both negative (257 and 415 MeV) and positive (411 MeV) pion production at θ_{lab} = 15° on target material. The lines through the data correspond to an $A^{1/3}$ dependence, as expected if the interaction occurs on the nuclear surface (peripheral). Results at θ_{lab} = 3° for 326 MeV negative pions also fit an $A^{1/3}$ dependence. They have also compared their data to a model involving pions produced in single nucleon-nucleus collisions with Fermi motion folded in. As in the earlier examples, assumptions about single-nucleon momentum distribution functions are required. Fig. 7b shows their data for π^- production at 15° from an Al target. The cross section is plotted against the current in the magnet used to measure the pion's momentum (for reference, 160 Amps is $T_\pi \sim$ 600 MeV). The solid

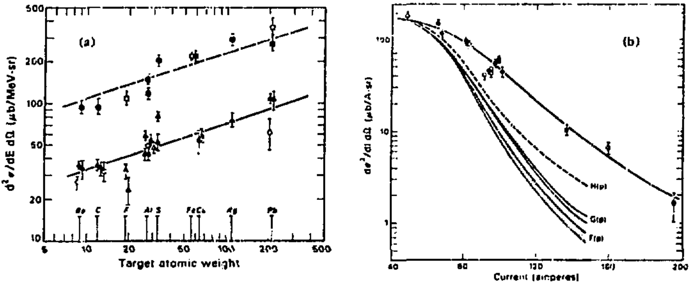

Fig. 7: (a) A-Dependence of pion production at 15° (lab) for ^{14}N experiment of Ref. 3: Squares (T_{π^-} = 257 MeV), triangles (T_{π^-} = 415 MeV), circles (T_{π^+} = 411 MeV).
(b) Differential cross section for π^-, production as function of current in momentum analyzing magnet.

curve through the data points represents a guide-to-the eye and the various labelled curves under the data correspond to different functional forms for the single-particle momentum distributions for projectile nucleons. The data and predictions agree for $T_\pi \lesssim 415$ MeV ($\sim$ 90 Amps) and disagree for larger values of the pion energy. It should be noted that for these measurements $x' \lesssim 0.1$, whereas the Berkeley and Dubna experiments were at larger values of x'.

For isospin-zero nuclei like deuterons, alphas, and carbon charge symmetry predicts that in the reactions $d + C \rightarrow \pi^\pm + X$ and $\alpha\ C \rightarrow \pi^\pm + X$ the π^+/π^- ratio should be one. This has been tested and found to be good to the level of ± 10% in the Berkeley data[1] for deuterons and alphas. The results of a Saclay experiment[6] using deuterons at 1.16 GeV see no violations at the level of ± 10% also. More accurate experiments will be required to test this further.

INDIRECT MEASUREMENTS OF PION PRODUCTION

Pions can result from the production of mesonic resonances (*e.g.*, $\eta, \rho, \omega, \ldots$) which subsequently decay into pions and other mesons. By observing a signal for the production of a resonance, one is then indirectly measuring pion production cross-sections. Nuclei with I = 0, such as deuterons or alphas, can play an important role in investigating the I=0 meson spectrum. Experiments like:

$$d\ d \rightarrow {}^4He + MM \quad (1)$$

or

$$d\ d \rightarrow d\ d + MM \quad (2)$$

guarantee that the MM spectrum is in an I=0 state. For example, one can look for ω-production and extract the $\omega \rightarrow 2\pi$ branching ratio without ρ-interference. Banaigs *et al*[7] have used deuteron beams at Saclay to study reaction (1). Fig. 8 shows a sample of their missing mass (MM) spectrum taken at an angle of $\theta_{lab} = 0.3°$. The sharp peak at $\sim$ 320 MeV corresponds to the production of the ABC effect.[8] This effect also appears in the reaction, $p\ d \rightarrow {}^3He + MM°$; but *does not* appear in the process,

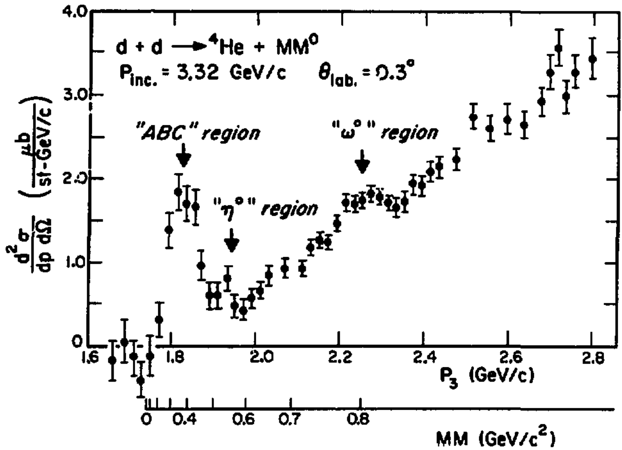

Fig. 8· Data of Ref. 7 for the reaction: d d → ^{4}He + MM° (p_d = 3.32 GeV/c, data at θ_{lab} = 0.3°).

p d → ^{3}H + MM$^+$. With these facts one is lead to conclude that the ABC is an I=0 effect. It does not appear to be real $\pi\pi$- resonance since it is not produced in πp and Kp interactions involving two pions in the final state. The bump near 800 MeV is in the region of the ω^0-meson. If this bump were due to the ω^0, it corresponds to a cross-section of 1.0 ± 0.3 nb/sr. Notice that there is no evidence for η^0-production. *Further experimental work is called for to determine the extent of and production* mechanisms for meson resonances in nuclear collisions.

Recently substantial theoretical work has been devoted to the question of the ABC effect.[9] A majority of these calculations essentially involve a nucleon-nucleon interaction, followed by a final state interaction forming the observed nucleus. Thus they are sensitive to such things as nuclear form factors. In a review of ABC theories, Barry[10] suggests that the ABC is associated with the excitation of the 3-3 resonance in nuclei.

The Saclay group[11] has used reaction (1) to search for, d+d → ^{4}He + π^0. Since the pion has I=1, the observation of this reaction serves as a test of charge symmetry in strong interactions. They obtained *an upper limit* for this cross-section of 1.9 x 10^{-35} cm^2/sr (for 1.89 GeV/c incident deuteron beam, and production angle of $\theta_{C.M.}$ = 79°). This is approximately a factor of 5 smaller than the previous limit (obtained at a different energy).

OTHER MEASUREMENTS OF INTEREST

Presently there is considerable theoretical interest in the possibility of creating abnormal nuclear matter[12], shock waves[13], or highly excited nuclear matter[14] in central collisions between nuclei. During these collisions it is expected that N*'s will be formed inside the nucleus and will decay yielding pions with characteristic kinetic energies of a few hundred MeV. The emission of such charged and neutral pions can serve as a convenient cooling mechanism for the highly excited nuclear matter. Some theoretical models suggest that a large number of pions will be emitted near 90° (C.M.) in these central collisions.

Observation of charged and neutral pion multiplicities should be useful in sorting out the dynamics of central collision processes. Such measurements require apparatus with a large solid angle for detecting pions, along with the ability to be highly selective. One possible device is a streamer chamber. A preliminary run with a 0.87 GeV/n carbon beam was recently performed at Berkeley.[15] Fig. 9 shows a stream chamber photograph of the carbon beam interacting with a lucite target. In this event two negative pions are produced (the tracks which are bent upward by the magnetic field of the chamber). With such pictures one can easily count the charged tracks and it is hoped that the energies of a majority of these tracks can be obtained. Particle identification will be made through a combination of energy loss and ionization devices external to the chamber.

Recently there has been theoretical speculations[16] on the N* composition of nuclear matter. Such states may be observed in nucleus-nucleus collisions.[17] If so, then the streamer chamber, will provide one possible tool for investigating them.

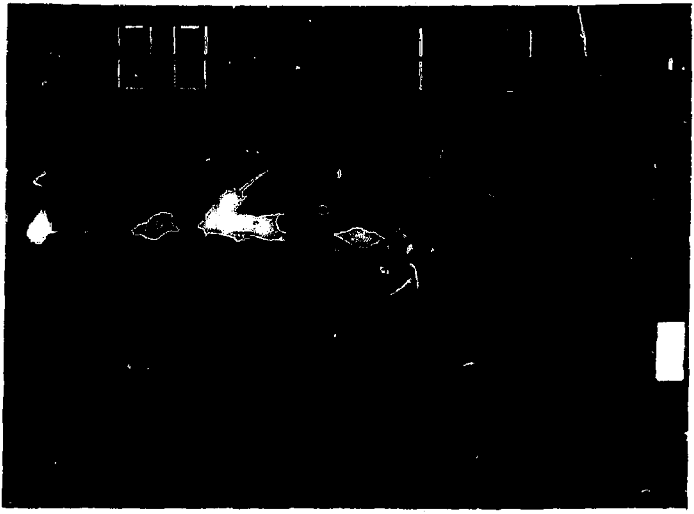

Fig. 9: Streamer chamber photograph of an 0.87 GeV/n carbon beam interacting with a lucite target. The incident carbon experiences a collision that can be characterized as central, since both target and projectile fragments are produced (the short thick tracks are target-related fragments). In addition, two negative pions are created. These are the tracks which are bent upward by the magnetic field of the chamber.

CONCLUSIONS AND FINAL COMMENTS

Presently, the experimental information on very high energy pion production has been obtained through single-particle inclusive measurements. These data have typically been restricted to energetic pions produced either by deuteron or alpha beams. The interpretation of the production mechanism for these pions is presently divided. The Berkeley group favors a nucleon-nucleus model with Fermi motion. The Dubna group states that their data is not consistent with such a model, rather they require a cooperative mechanism among several nucleons. Clearly additional experiments are required to resolve this point. In any case, the production of high energy pions should provide a valuable probe for obtaining new information on the high-momentum components of nucleons inside nuclei. Thus, it offers yet another way of studying the correlations of these nucleons.

It will be interesting to observe very high energy pions produced by heavier incident nuclei. Will the production mechanisms be similar to those found for deuteron and alpha beams, or will the presence of many more nucleons modify the picture? To do these experiments will require large fluxes of the heavier ions, a possibility which is now being realized. The existing data for p,d,α production of negative pions shows that scaling has set in as low as 1 GeV/nucleon. Again, will this persist for heavier nuclei? The A-dependence of high energy pions has been found to be consistent with $A^{1/3}$, suggesting a peripheral production mechanism. What will it be for more central collisions? Copious pion production will result in these central collisions. Multiplicity measurements, energy and angular distributions of the pions should be helpful in sorting out the possible existence of abnormal nuclei, shock waves, and highly excited nuclear matter. Studies of multipion final states can be expected to provide information on the role of other mesons ($\eta,\rho,\omega,\phi,\ldots$) in nuclei.

The early experiments on pion production have probably ended up asking as many questions as they have answered. The experiments are not easy and neither are the theoretical interpretations. However, such studies can be expected to yield new insight into the interactions of nuclei at the highest energies.

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