PHYSICAL REVIEW C VOLUME 31, NUMBER 1 JANUARY 1985

Inclusive pion production in 330, 400, and 500 MeV proton-nucleus collisions

N. J. DiGiacomo, M. R. Clover, R. M. DeVries, J. C. Dousse,* J. S. Kapustinsky, P. L. McGaughey, W. E. Sondheim, and J. W. Sunier
Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

M. Buenerd and D. Lebrun
Institut des Sciences Nucléaires, 38026 Grenoble Cedex, France
(Received 22 June 1984)

We present measurements of the inclusive $\pi^{\pm}$ momentum distributions and total pion production cross sections for 330, 400, and 500 MeV protons incident on ^{12}C and ^{238}U. The π^+/π^- cross section ratio is seen to increase sharply with decreasing projectile energy for the light nucleus. Comparisons are also presented of the projectile energy systematics of data and intranuclear cascade calculations in the intermediate energy region.

The study of pion production in proton-nucleus (pA) and nucleus-nucleus (AA) collisions now forms a major subfield of intermediate energy physics, with three proton-beam "pion factories" (LAMPF, TRIUMF, and SIN) and one nuclear beam facility (LBL BEVALAC) in operation. A pion in the final state of a nuclear reaction is of interest for reasons ranging from the unique momentum transfer and quantum-number matching possibilities to the simple fact that a pion must come from a rather energetic interaction in a nucleus.

The current picture of pion production and propagation in nuclei emphasizes the dominant role of the Δ_{33} resonance, particularly in determining gross observables such as inclusive nucleon and pion yields in pA and AA collisions. Other dynamical input integral to a quantitative description of pion production and propagation includes charge exchange for both projectile and ejectile, pion absorption channels, and the relevant nuclear structure details. The intranuclear cascade (INC) approach,[1-9] and related models to a great extent,[10,11] propose to include the necessary physics by assuming a series of on-shell incoherent hadron-hadron (e.g., NN, ΔN, or πN) collisions. Success in describing pA and AA interactions is good, particularly, again, for inclusive observables.[1-7] Adapted to AA collisions,[8,9] the INC is used as a background in order to search for strong collective effects not, by definition, contained in the INC but postulated to occur due to the use of a composite projectile. The INC approach has a number of conceptually attractive features, not the least of which is the fact that it is based primarily on measured experimental cross sections for fundamental processes. Also, because the calculation proceeds in a timelike fashion, each cascade is stored and can be used to extract detailed information on the evolution of the interaction. This has, in fact, been rather well exploited in studies of intermediate energy AA collisions.[12]

We have long been concerned, however, that the present theoretical picture, as contained in the INC, has not been adequately tested for pA inclusive pion production below approximately 600 MeV incident energy due to a lack of data. The only extensive measurements of inclusive pion production in pA collisions are at 730 and 585 MeV.[13-15] This is in marked contrast to the AA situation where many data exist, particularly at $E/A = 400$ MeV.[16] We find ourselves, then, in the rather disconcerting situation that the INC approach, having not really been tested on the conceptually and computationally simpler pA inclusive pion production, is used extensively to understand AA pion production. Indeed, it is also possible that new physics lurks in this unexplored pA energy regime. Thus motivated, we undertook the measurements described here.

The experimental apparatus we used is rather novel, with some advantages over conventional spectrometers, the most obvious of which is the ability to detect (among other particles) $\pi^{\pm}$ for $-180° \le \theta_{lab} \le +180°$ simultaneously. It was designed, in fact, to measure the more complex multiparticle final states expected when antiprotons annihilate on nuclei. Parts of the device have been described elsewhere,[17,18] and a complete description will appear in the proper journal.

The spectrometer consists of a 81-cm diameter, 7.5-cm gap dipole magnet run at 8 kG with a thin (~ 750 mg/cm^2) target situated at the center. The pole gap is surrounded by six detector modules, each approximately 50 cm from the target, and capable of independently providing momentum, energy loss (ΔE), time-of-flight (TOF), and Cherenkov information. The beam travels through a narrow vacuum chamber with 0.13 mm Mylar walls, and passes between two detectors upon entrance and exit of the pole. The beam is counted, and TOF started by a thin scintillator upstream of the target. Beam definition is accomplished by a variety of scintillator veto counters, and beam position on target is assured by thin wire chambers at the entrance and exit of the pole. The overall acceptance is approximately 0.5 sr, and beam rates are generally less than 2×10^6/sec.

Each detector module consists of a plastic Cherenkov detector,[18] a plastic ΔE detector, and two planes of helical delay line (x), and individual wire readout (y) gas proportional counters. Momentum resolution varies from 1% to 6% depending on the ejectile momentum.

Event analysis and reconstruction is rather complex, due to the mix of θ_{lab} and p_π that a given detector sees. The raw momentum and scattering angle reconstruction is done interactively on the MODCOMP 7860 computer that also served to acquire the data. The remainder of the event analysis, including corrections for target energy loss, detector solid angle, momentum resolution, and dead time, is performed at the Los Alamos Central Computing Facility.

The measurements presented here were made at the BL1B line at TRIUMF. Beam size averaged 7×7 mm^2, with negligible divergence. Careful attention was paid to sources of background such as multiple scattering on the poles or vetoes around 0°. The excellent redundancy of the system allow separation of $\pi^{\pm}$, $e^{\pm}$, p, d . . . , over a large dynamic range, and the broad acceptance in p and θ makes integration to obtain $d\sigma/dp$ or $\sigma_{\pi}\pm$ quite reliable. We estimate an overall normalization uncertainty of $\pm 10\%$, but emphasize that there should be no systematic π^+/π^- differences, as both were measured simultaneously with the same detectors.

The experiment determines $d^2\sigma/d\Omega\, dp_{\pi}$ for $-180° \leq \theta_L \leq +180°$ (i.e., detectors at +/− angles) and $p_{\pi} \geq 100$ MeV/c with gaps in (p,θ) here and there due to mechanically dictated spaces between detectors. The relatively isotropic $d^2\sigma/d\Omega\, dp$ at each momentum bin is interpolated to fill these gaps, integrated over angle, and the results for π^+ production are presented in Fig. 1. These momentum distributions are then integrated over momentum (and extrapolated to 0 cross section at the Coulomb barrier for π^+ and at $E_{\pi}=0$ MeV for π^-) to give $\sigma_{\pi}\pm$ and the π^+/π^- ratios shown in Fig. 2. The functional form of the extrapolation was chosen to be consistent with measured low-energy pion yields.[15] The error bars on the present $\sigma_{\pi}\pm$ total cross sections and π^+/π^- ratios given in Fig. 2 reflect both statistical and systematic (e.g., extrapolation) errors, with the latter being dominant.

The INC calculations were performed with the code ISABEL.[8,9] This code has evolved from VEGAS[1-5] through confrontation with a broad range of nucleon, pion, and nucleus-induced reaction data, and has, to date, been successful in describing inclusive pion and nucleon yields in proton and pion induced reactions on nuclei.[1-7] For example, the 730-MeV data[13] are well reproduced by an earlier VEGAS calculation.[5]

The present data allow for the first time a complete picture to emerge of the projectile energy dependence of proton-nucleus inclusive pion production in a range relevant to both intermediate energy nucleon and heavy-ion induced pion physics. Note that the π^+/π^- ratio rises quite strongly for ^{12}C (Fig. 2) but remains rather flat for ^{238}U, indicating the importance of Δ rescattering and charge exchange in enhancing π^- yield for the heavier nucleus. The $\pi^{\pm}$ total cross sections are seen to drop approximately one order of magnitude between 730 and 330 MeV, with the ^{12}C π^- yield dropping rather more quickly than the others below 500 MeV. This latter fact gives rise to the increase in the ^{12}C π^+/π^- ratio with decreasing proton energy and implies that the pion production mechanism in ^{12}C approaches pure quasifree Δ production as the projectile energy decreases.

Rather unexpectedly, the INC calculations fail to quantitatively reproduce the total π^+ and π^- yields from ^{238}U at the lower bombarding energies, whereas the agreement between

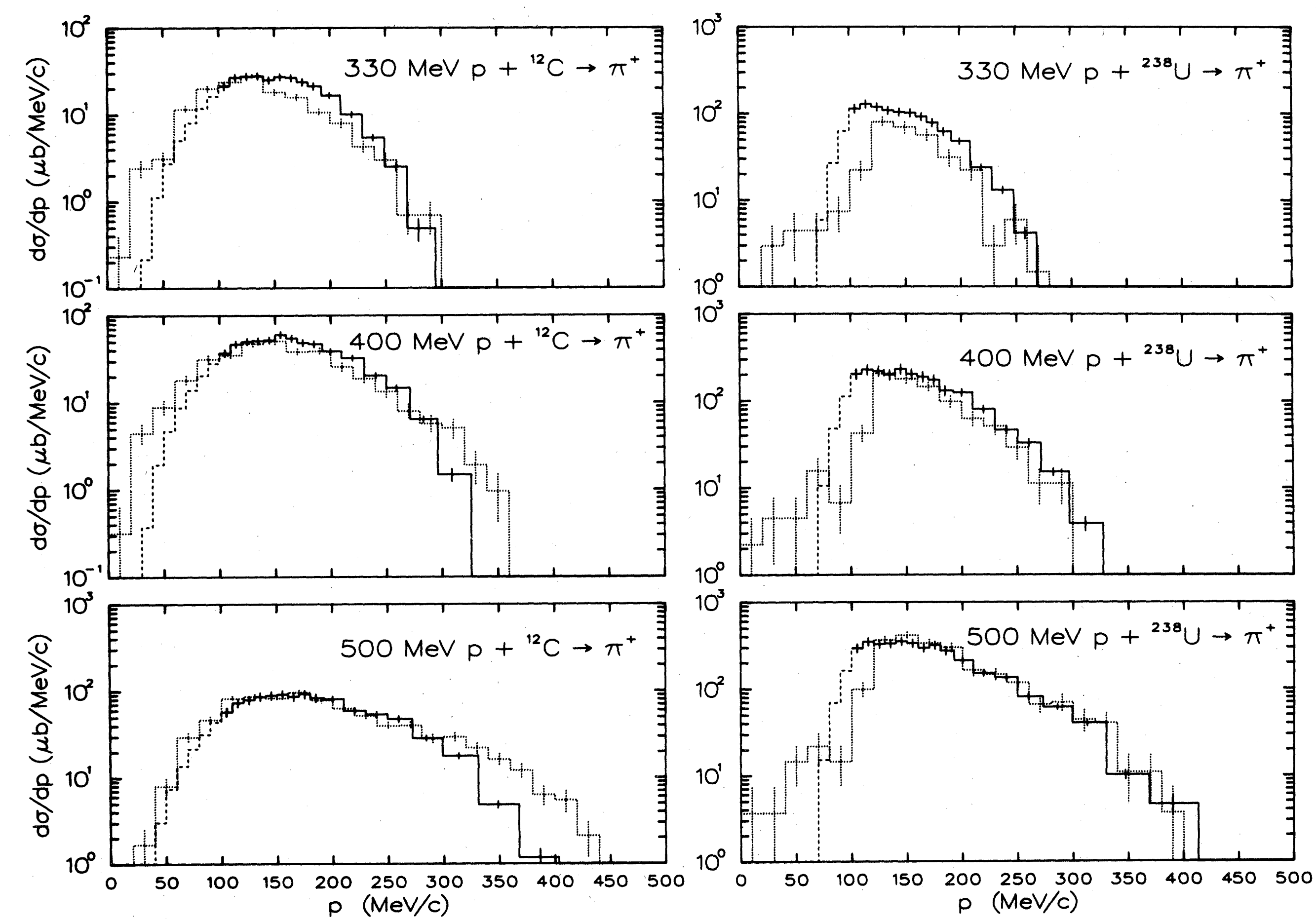

FIG. 1. The angle integrated inclusive momentum distributions for π^+ resulting from protons incident on ^{12}C and ^{238}U. The solid curves represent the present measurements while the dotted curves show the results from the INC calculations described in the text. The dashed curves are extrapolations used to obtain an upper limit for $\sigma_{\pi}\pm$ (see text).

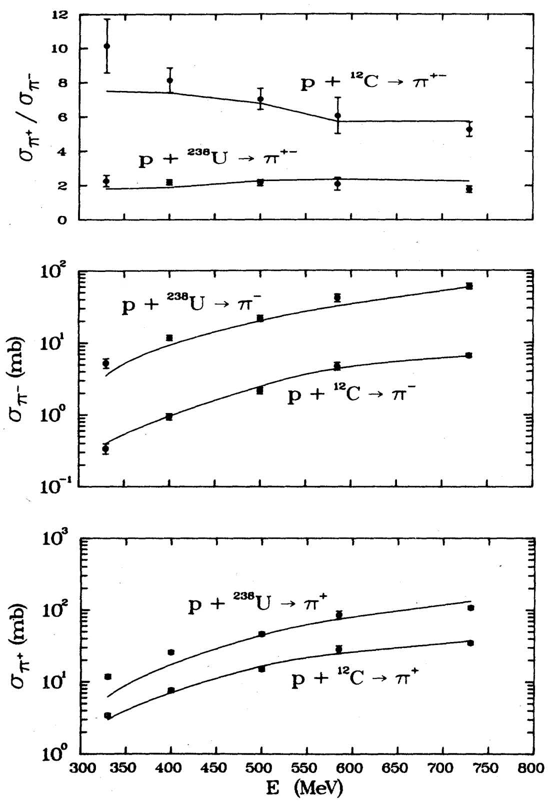

FIG. 2. The total cross sections and ratios for $\pi^{\pm}$ production in proton collisions with nuclei are shown vs incident proton energy. The data at 330, 400, and 500 MeV are the present measurements on ^{12}C and ^{238}U, while the points at 585 MeV (Ref. 14) are from ^{12}C and ^{208}Pb and the 730 MeV (Ref. 13) data are from ^{12}C and ^{232}Th. See text for an explanation of the error bars. The solid lines connect INC calculations for each of the corresponding experimental measurements.

the INC and the data is excellent in all cases above 500 MeV. The underprediction of yields for ^{238}U is seen (Fig. 1) to occur for all pion momenta, with perhaps an emphasis on $E_\pi \lesssim 125$ MeV. In addition, the INC shows a one-to-two standard deviation disagreement with the π^+/π^- ratio rise at 330 MeV. Less surprisingly, the INC also has difficulty at low pion energies (Fig. 1), e.g., yielding a small number of π^+ in the region below the Coulomb barrier. These pions were found to be artifacts of a prescription in the calculation used to force the decay of very slow Δ's at the nuclear surface in order not to spend an excessive amount of computer time tracking them.

The present measurements raise questions concerning the INC's ability to quantitatively reproduce inclusive pion production over an incident energy range directly relevant to intermediate energy nucleus-nucleus studies. How much this implies the action of physical processes over and above those presently included in the INC and how much it reflects input inadequacies in the code[19] becomes more difficult to ascertain as the projectile energy decreases because of the inherent inefficiency of applying the Monte Carlo technique to low cross-section processes. Calculations using the techniques of Refs. 10 and 11 must be extended to lower proton energies in order to answer this question.

In summary, we note that the experimental results presented here close the gap between the threshold pion production region[20,21] and the well studied range above 600 MeV in p*A* interactions. The data now exist to test models of proton induced pion production by nuclei (including, but of course not limited to, the INC) over the projectile energy range from threshold to almost 800 MeV.

The authors are indebted to Ewart Blackmore, Jim McElroy, and the TRIUMF staff for making the experiment possible. We are also grateful to Yair Yariv for discussions concerning the INC. This work was supported by the U.S. Department of Energy and by the North Atlantic Treaty Organization.

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*Permanent address: Université de Fribourg, Fribourg, Switzerland.

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