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## Gross and Fine Structure of Pion Production Excitation Functions in p-Nucleus and Nucleus-Nucleus Reactions

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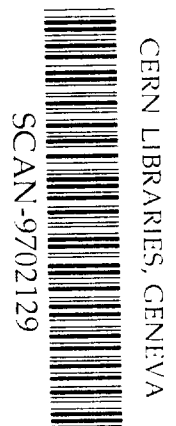


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## Abstract

Slow ramping of the CELSIUS storage ring has been utilized to measure the yield of charged pions in proton and heavy ion induced collisions with continuously varying beam energy. BUU predictions, including Fermi momenta of nucleons in nuclei, overestimate the backward emission but follow the general shape of the excitation functions quite well except very close to the absolute threshold. No statistically significant narrow resonances are observed.

Pions can be produced in hadron-nucleus and nucleus-nucleus collisions, even at energies well below the free nucleon-nucleon (NN) threshold through the collective interaction between several nucleons or through the boost from the internal nucleon momentum. Suggested production mechanisms range from first chance NN scattering [1, 2], full cascade prescriptions [3, 4], dynamical mean-field + NN collision equations [5, 6, 7, 8] and cluster-cluster interactions [9] to fully collective pionic fusion models [10, 11, 12]. The strong rescattering when pions or deltas propagate through the nuclei must of course be introduced in all models.

Many of these models predict the overall features of pion emission well but a detailed selection among them is hampered by the lack of systematic data. By combining slow ramping operation of the CELSIUS storage ring with range telescope technique, complete excitation functions for  $\pi^\pm$  emission over wide ranges of beam energy can be measured as shown in this paper.

Protons and fully stripped Ne ions were injected into the CELSIUS storage ring [13], accelerated up to the start energy, stored during slow ramping of the magnets with gas-jet target in operation until the final energy was reached, and then finally dumped. The cycle time, 2-5 min, was governed by the requirement that at least 1/3 of the stored ions should remain. Data were collected continuously during 70 - 250 s. The start time for slow ramping, the time when the event trigger appeared and the beam frequency at that time was stored to provide the collision energy. No electron cooling of the beams was introduced. Data from two ramp cycles, one at low energy (169-270 MeV for p and 50A-120A MeV for Ne) and one high energy (250-500MeV and 100A-400A MeV), were put together. The reproduction of the cycles was very good and data could be added for several hours without increasing the collision energy dispersion ( $<0.8$  MeV for proton beams and  $<0.9A$  MeV for Ne beams). Gas-jet target thicknesses of between  $10^{13}$  and  $10^{14}$  atoms/cm<sup>2</sup> for N, Ar, Kr and Xe gases were employed.

Five 9-element plastic range telescopes were mounted outside thin steel windows in angular positions from 20° to 120°. These telescopes are of standard "CHIC construction" [14] with increasing scintillator thickness to obtain equally broad pion energy bins. The  $\pi^+$  is identified through pulse shape discrimination technique, utilizing the delayed muon energy signal from the 26 ns,  $\pi \rightarrow \mu\nu$  decay [14].

Since the momentaneous luminosity cannot be measured, high energy protons (52-161 MeV) were registered, together with pions in the range telescopes, to obtain absolute normalization (last term in eq. (1)). Since proton (+ heavy particle) rejection [14] was required in the p - nucleus experiment (99% efficiency), calibration runs were performed with rejected and non-rejected protons registered simultaneously in

two identical telescopes placed at  $90^\circ$  on each side of the beam direction. The total high energy proton yield is translated into absolute cross-sections via empirical information [15,16] normalizing standard BUU [8] or cascade calculations [17] (BUU finally used here). The pion cross section is given by,

$$\frac{d\sigma_\pi}{d\Omega} = f_{eff} \cdot \frac{N_\pi}{N_p} \cdot \Delta\Omega \cdot \left( \frac{N_{\pi nr}^c}{N_{\pi r}^c} \frac{N_{pr}^c}{N_{pnr}^c} \right) \cdot \int_{52}^{161} \frac{d^2\sigma_p}{d\Omega dE} dE. \quad (1)$$

The efficiency factor,  $f_{eff}$ , contains corrections for decay in flight and during slow-down in detector material, pion scattering in the detector material and geometry for muon capture [18]. The quantity  $\Delta\Omega$  is the relative solid angle correction, c stands for calibration telescope, r for rejection and nr for non-rejection (of protons). The rejection term, within brackets in eq. (1), is pion energy dependent and parametrized as  $\sim a \cdot \exp(-b E_\pi)$  from the seven values obtained from particles that stop in telescope elements 3-9.

Figure 1 presents examples of differential ( $d\sigma/d\Omega$ ) cross sections of  $\pi^+$  emitted at  $97^\circ$  in  $p + {}^{40}\text{Ar}$  and  $p + {}^{nat}\text{Xe}$  reactions. Fig. 1a shows the  $p + \text{Ar}$  excitation function with 1 MeV beam energy binning. A rather large difference in statistics between the low-energy and high-energy data sets for  $p + \text{Ar}$  introduces the large differences in statistical fluctuations which is not the case for  $p + \text{Xe}$  where statistics is comparable between the data sets (Fig. 1c). The normalizing procedures may introduce different systematic errors for the low and high energy data and therefore we normalize the data sets in the overlapping region to the set with the highest statistics. In no case is there a mismatch between the low energy and high energy data sets exceeding 20%. The error in absolute yield is ranging from 30% to 50% (for the lowest beam energy).

The long arrows in Fig. 1 mark the absolute (kinematical) threshold for the reaction,  $p + X \rightarrow \pi^+(E_\pi > E_\pi^{min}, \Theta=97^\circ) + \dots$ , which is calculated from the general threshold condition related to the available c.m. energy,  $E_{av} > m_\pi$  where,

$$(E_{av} + m_A + m_B + m_\pi)^2 = (\gamma_A m_A + \gamma_B m_B + \gamma_\pi m_\pi)^2 - (\vec{\beta}_A \gamma_A m_A + \vec{\beta}_B \gamma_B m_B + \vec{\beta}_\pi \gamma_\pi m_\pi)^2. \quad (2)$$

The short arrows denote the experimental cut-off. The background is very small and appears to be flat in the region below the absolute threshold (see Fig. 1b). Fig. 1b also shows that pions with  $E > 57$  MeV are observed even at the lowest possible 1 MeV beam energy bin.

Figure 2 gives differential  $\pi^+$  cross sections in  $p + \text{Ar}$  collisions at three angles and in  $\text{Ne} + \text{Ar}$  collisions at two angles. All data are compared to BUU (Boltzmann Uehling-Uhlenbeck) calculations with "default" input parameters from [8, 19].

The numerical BUU implementation is based on the test particle method and uses the parallel ensemble algorithm. 1000 (p) and 500 (Ne) test particles/nucleon have been used. The Fermi momentum of each test particle is given a local value,  $P_F = \hbar(\frac{3}{2}\pi^2\rho(r))^{\frac{1}{3}}$ . The initial momentum is chosen either from a sharp sphere homogeneous distribution or from a Gaussian distribution that correctly describes the high momentum components in heavy ion data on particle emission. Nucleons and resonances propagate in a density dependent (Skyrme) mean-field,  $(U(\rho) = A(\rho/\rho_0) + B(\rho/\rho_0)^\sigma$  where  $A=-124$  MeV,  $B=70.5$  MeV,  $\sigma=2$ ,  $\rho_0=0.168$ ), + Coulomb potential. Pions, produced through  $\Delta$  and  $N^*$ , are treated as free particles interacting with the Coulomb potential only. Reabsorption is taken into account through the process,  $N + \pi \rightarrow \Delta$ ,  $\Delta + N \rightarrow N + N$ . Resonance decay is isotropic and pions as well as nucleons face two-body elastic and inelastic collisions, taking Pauli blocking into account. The calculations proceed for 100 fm/c in 20 (pA) or 10 (AA) impact parameter steps.

It appears as if this version of BUU overestimates the pion yields. Introducing a  $\Delta$  decay distribution, which is backward peaked at low energies and forward peaked at higher energies[20] as suggested in ref. [21], does not decrease the discrepancy very much. The introduction of Fermi motion is necessary to reproduce the low energy data (open squares in Fig. 2) whereas the degeneracy of the Fermi distribution (black points) improves the agreement marginally. It should be stressed that for energies below 200 MeV in pA or 150A MeV in heavy ion collisions, the calculations tend to drop much faster than the data (no points because of too long computer execution time).

Figure 3 shows the total yield of  $\pi^+$  from p + N and p + Ar collisions. The necessary correction for missing low and high energy pions (5% at low and 50% at high beam energies) is introduced from BUU calculations with a Gaussian internal momentum distribution.

The experimental ratio between the p +  $^{14}\text{N}$  and the p +  $^{40}\text{Ar}$  yield decreases from 2.9 (corresponding to a  $A^{1.01}$  dependence) at the lowest energies to 1.5 ( $A^{0.40}$ ) at the highest, indicating a trend to go from a strict volume dependence to nearly a disc dependence, characteristic for peripheral interactions. A comparison to the most systematic data set, reported in the literature, is made. The agreement between these p +  $^{12}\text{C}$  data and the p + N data is satisfactory for higher beam energies but below the free NN threshold (290 MeV) there is up to a factor of two difference although an  $A^{2/3}$  dependence would predict only a factor of 1.11. Statistical errors cannot explain this difference but with respect to the systematic errors in the experiments the difference is hardly significant.

Data on yields from a continuously varying beam energy, are ideal in the search

for sharp resonances, provided that high enough statistics can be obtained. Since the beam energy dispersion is  $< 1$  MeV, very narrow resonances should be possible to observe. One candidate has been reported in external target experiments,  $\pi^+$  emission at  $90^\circ$  in  $p + \text{Cu}$  reactions at an energy of  $350 \pm 1$  MeV [26-28]. The dibaryon explanation [23], has been rejected due to the narrow width,  $\sim 1.5$  MeV, which does not agree with the dispersion introduced by Fermi motion. More recent explanations include two-pion[26] and two- $\Delta$  [24] or  $\Delta$ -ball [27, 28] states.

One recent experiment [25] observed an even stronger signal when ratios of low energy to high energy pions,  $R$ , were explored. In Figure 4 we plot  $R = N_\pi(16 - 38 \text{ MeV})/N_\pi(38 - 75 \text{ MeV})$  for  $\pi^+$  emission at  $97^\circ$  in  $p + \text{Ar}$  and  $p + \text{Kr}$  reactions. Figs. 4a and 4c show the ratio with 1 MeV beam energy binning, in those regions where statistics allow it ( $> 250$  MeV), whereas a larger bin width (4-12 MeV) is presented in Figs. 4b and 4d. The general trend of decreasing  $R$  with increasing beam energy is a natural consequence of the kinematics but apart from this, there appears a number of peaks, the most intriguing being the one at 355 MeV in the  $p + \text{Kr}$  reaction (Fig. 4c). This is totally washed out in the 4 MeV binning representation (Fig. 4d). The value and statistical error of this peak is  $R = 0.95 \pm 0.22$ , with the "background" level at  $R = 0.49 \pm 0.08$ . The peak is thus only 2 S.D. above the normal level while the peak-to-background ratio is 2.1, as compared to the ratio 1.3 reported in [25] for the  $N_\pi(14.4-32 \text{ MeV})/N_\pi(38 - 80 \text{ MeV})$  ratio in  $p + \text{Cu}$ . Thus we cannot claim that the 355 MeV peak is observed but instead conclude that at least 10 times higher statistics is needed to settle this question.

In conclusion, we have demonstrated the power of experiments with slowly ramped beams and gas-jet targets at storage rings. The pion production excitation functions, both in  $p$  - nucleus and nucleus - nucleus collisions, agree in beam energy dependence but not in absolute yield with standard mean-field + NN collision models (BUU). This kind of approach also fails to reproduce the cross section at the lowest energies. No statistically significant peaks that indicate narrow resonances are observed, although one candidate -  $\pi^+$  emission at  $97^\circ$  in  $p + \text{Kr}$  reactions at 355 MeV - has been discussed.

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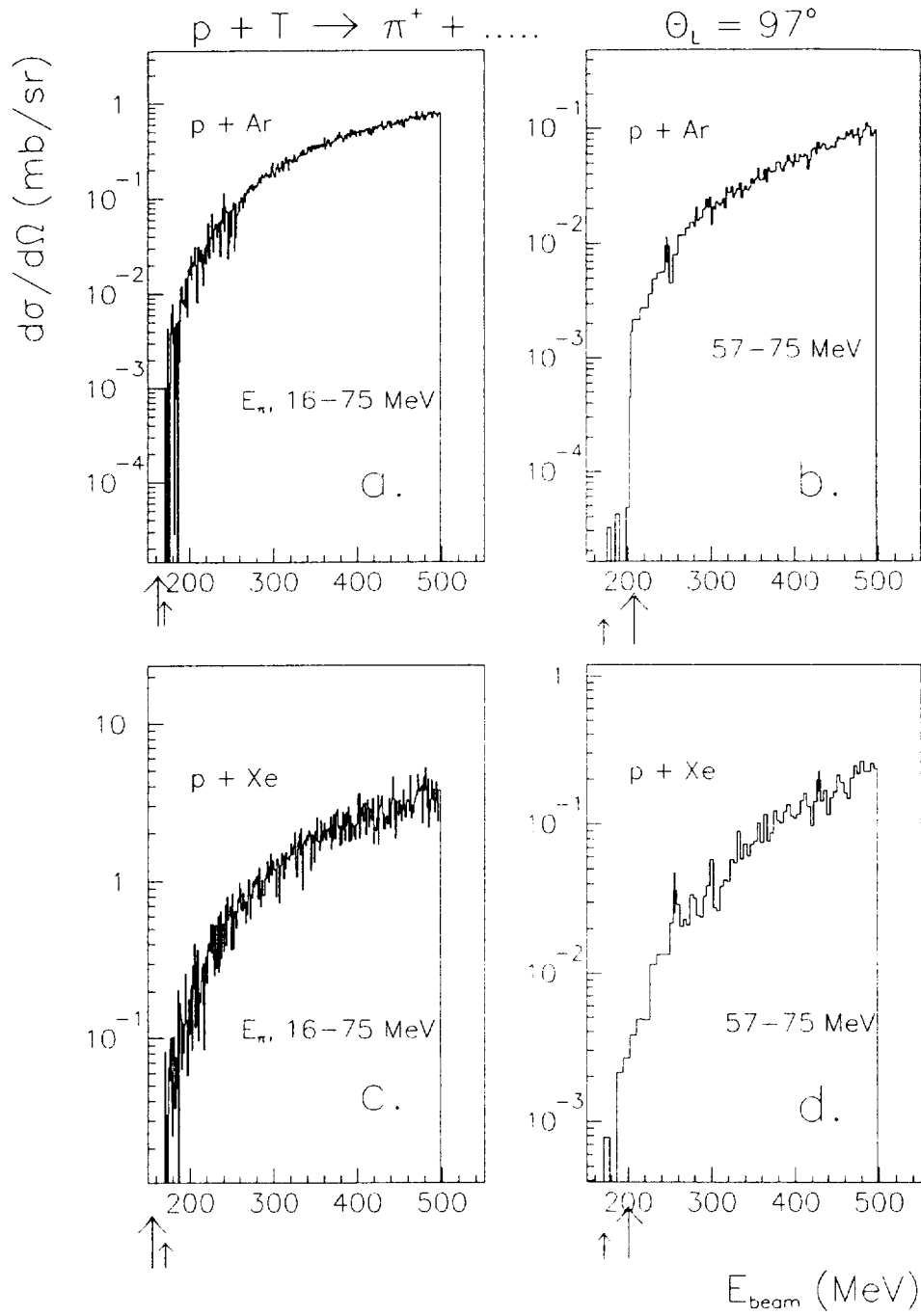


Fig. 1: Differential ( $d\sigma/d\Omega$ ) cross sections of  $\pi^+$  emitted at  $97^\circ$  in  $p + {}^{40}\text{Ar}$  and  $p + {}^{nat}\text{Xe}$  reactions. The beam energy binning is 1 MeV in 1a+c, 2-4 MeV in 1b and 4-8 MeV in 1d. The arrows indicate the absolute threshold and the experimental threshold, as explained in the text. The typical error bars in 1b+d are purely statistical.

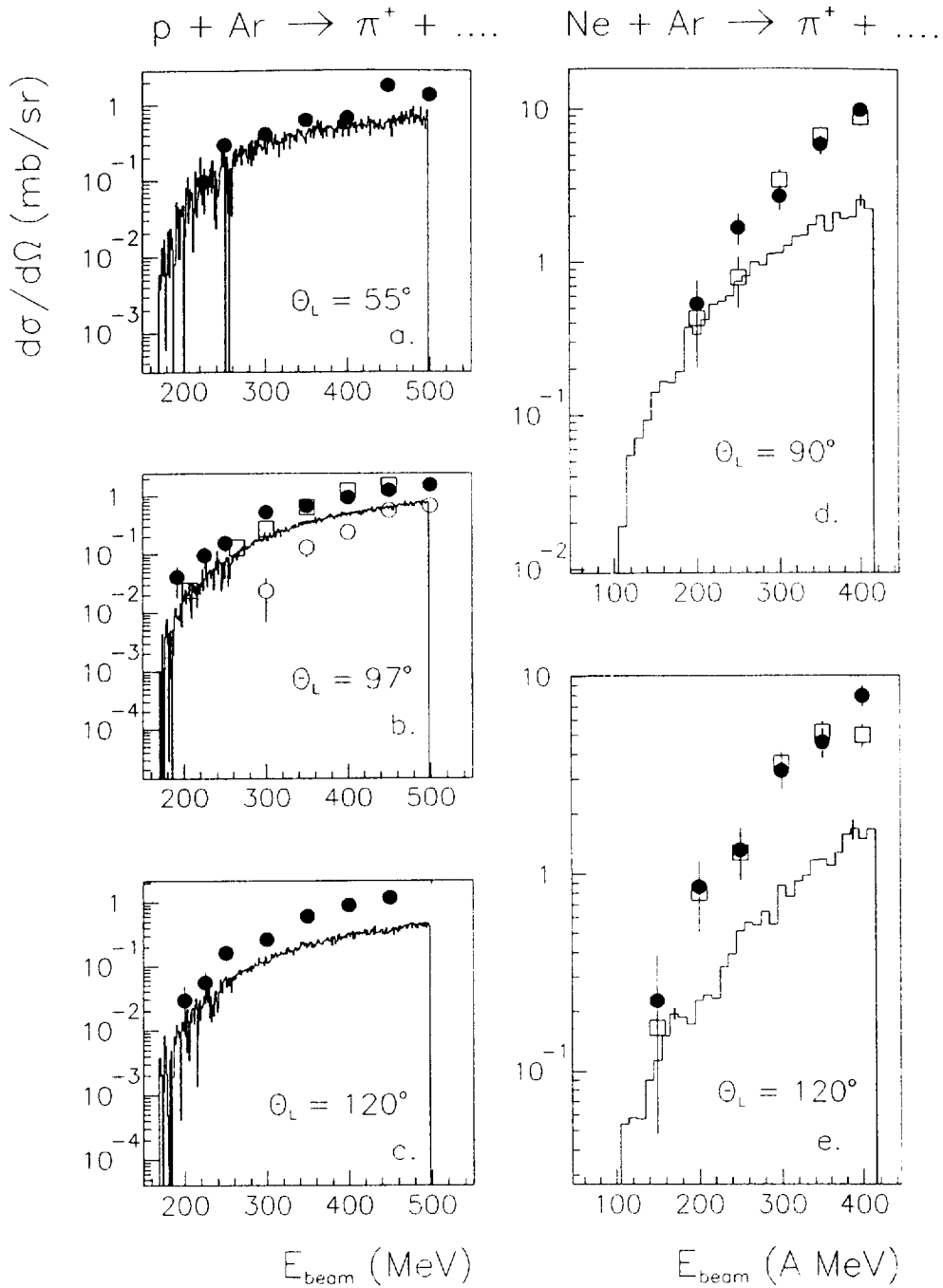


Fig. 2: Differential  $\pi^+$  cross sections in  $p + \text{Ar}$  collisions at three angles ( $55^\circ$ ,  $97^\circ$ ,  $120^\circ$ ), and in  $\text{Ne} + \text{Ar}$  collisions at two angles ( $90^\circ$ ,  $120^\circ$ ). The points represent BUU calculations where the momenta of the test particles is taken from a Gaussian distribution (filled circles), a homogeneous spherical distribution (open squares) or set to zero (open circles)

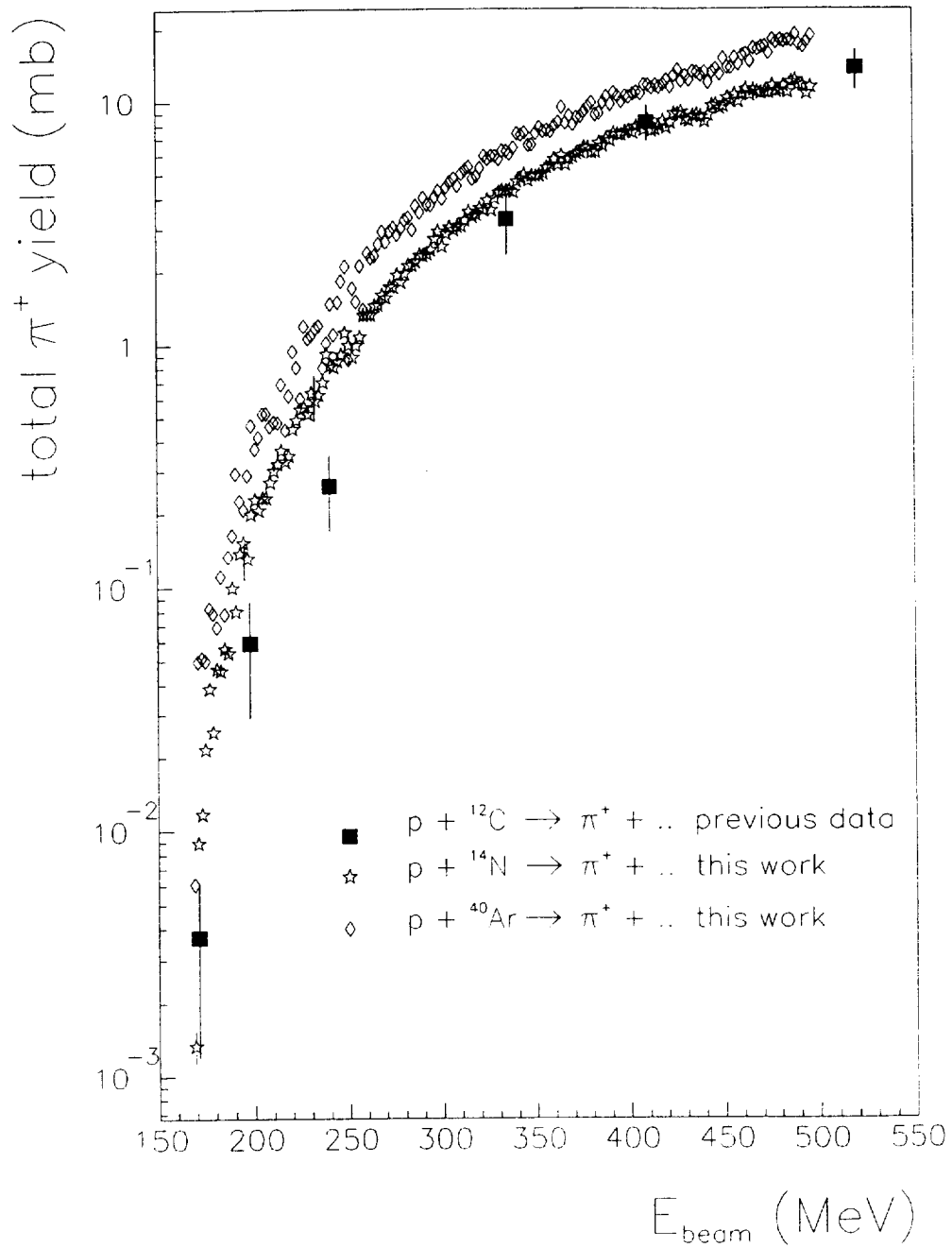


Fig. 3: Energy and angle integrated yield of  $\pi^+$  from  $p + N$  (stars) and  $p + \text{Ar}$  (diamonds) collisions. The solid squares are data taken for  $p + \text{C}$  reactions [22], in earlier experiments. Note the typical statistical errors in two  $p + N$  points.

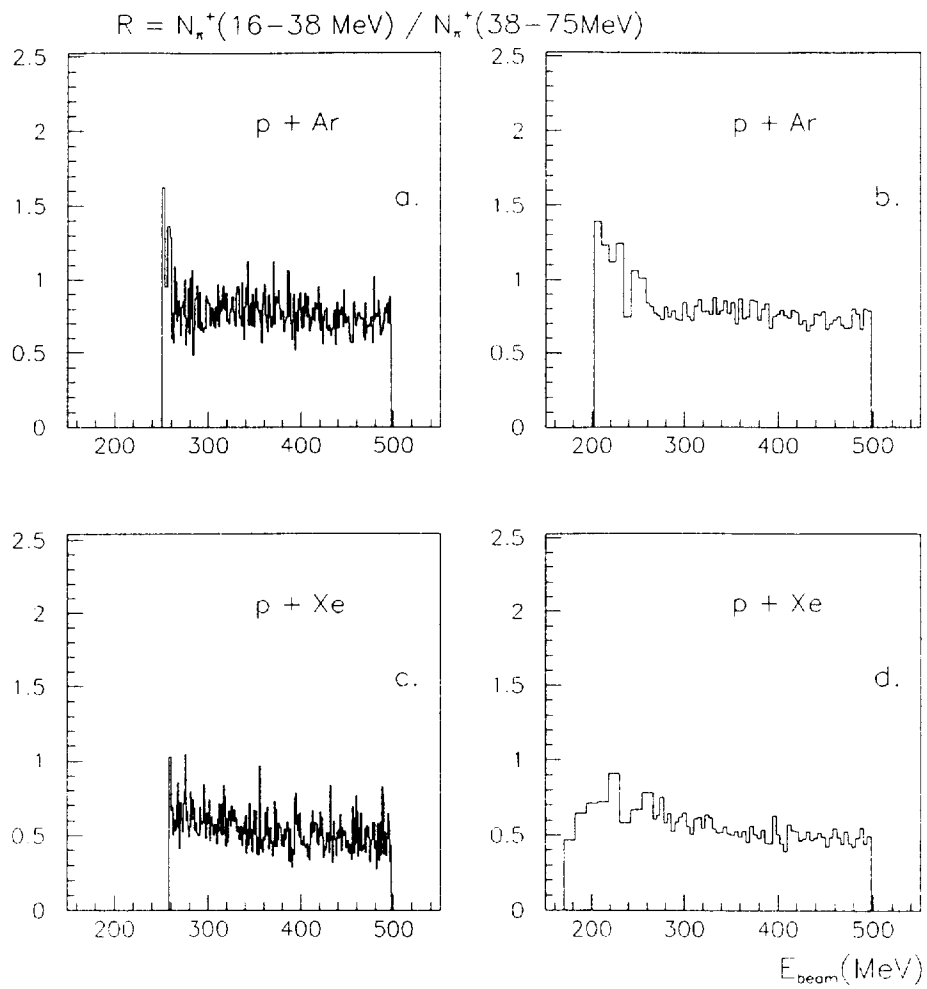


Fig. 4: Ratio between  $\pi^+$ , emitted at  $97^\circ$  in  $p + \text{Ar}$  and  $p + \text{Kr}$  reactions, with a kinetic energy of 16 - 38 MeV and 38 - 75 MeV. The beam energy binning is 1 MeV in panels a and c, 4 - 12 MeV in panels b and d.