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Low-Energy Pion Production at 0° with Heavy Ions from 125 to 400 MeV/Nucleon

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The results of a systematic study of 0° pion production by heavy ions from 125 to 400 MeV/nucleon are presented. The dependence of the cross section on the mass number of the target, the energy of the beam, and the pion charge and energy are discussed. A striking feature of the data is an unexpectedly large π^-/π^+ ratio for pions of velocity close to the projectile velocity.

There has been much speculation in recent years on the possibilities of a variety of qualitatively new nuclear phenomena[1-4] which may be observable with the pions produced in heavy-ion collisions. Detailed studies of pion production in such collisions with beam energies below ~1 GeV/nucleon are currently being carried out by several groups[5-8] to quantify the pion-production reaction mechanism and possibly to discover one of these new phenomena. In this Letter we present the first results from an experiment designed for pion measurements in a kinematic regime not previously investigated in heavy-ion experiments, namely, pions emitted at 0° with near-zero kinetic energy in the center-of-mass and projectile frames.

The 180° magnetic spectrometer used in this work has permitted measurements of both π^+ and π^- emitted with kinetic energy between 34 and 155 MeV in the laboratory system. At 400 MeV/nucleon this includes pions emitted with energies well below the Coulomb barrier in the center-of-mass and projectile frame. An unexpected result of these measurements is the very sharp and large anomaly in the π^-/π^+ cross-section ratio R displayed in Fig. 1. Additional results made possible by this apparatus include quantitative measurements of pion-production cross sections at heavy-ion-beam energies much lower than previously possible, far below the threshold for pion production in free nucleon-nucleon collisions and even below the threshold for nucleon-nucleus collisions. Spectra of π^+ and π^- have been recorded at 0° for Ne + NaF at five beam energies from 125 to 400 MeV/nucleon. Some data were also taken on Cu and U targets and at angles out to 30°.

The differential cross section at 0° varies by about four orders of magnitude over the beam energy range studied, and at the lowest energy, 125 MeV/nucleon, the pion yeild corresponds to less than one pion per 1000 nuclear interactions. The data are summarized in Fig. 2 and will be discussed further below. Preliminary theoretical considerations, also given below, indicate that a single production mechanism cannot account for the large variation of cross section over this range of beam energies.

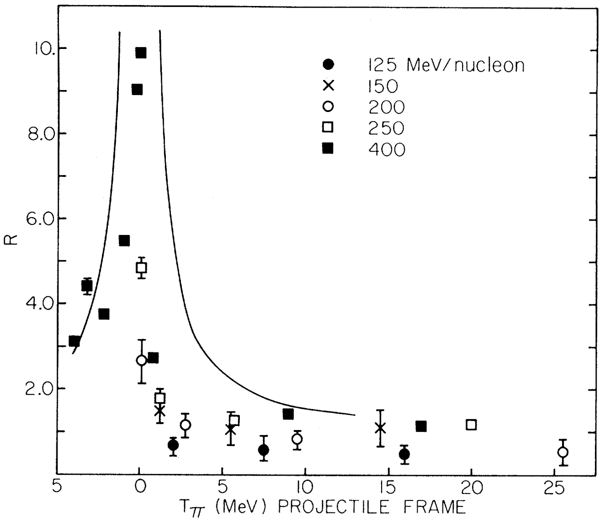

FIG. 1. Ratio, R, of π^- to π^+ cross sections in Ne + NaF (0°) as a function of pion energy in the projectile frame. The solid curve shows the Coulomb ratios calculated in the projectile frame as described in the text.

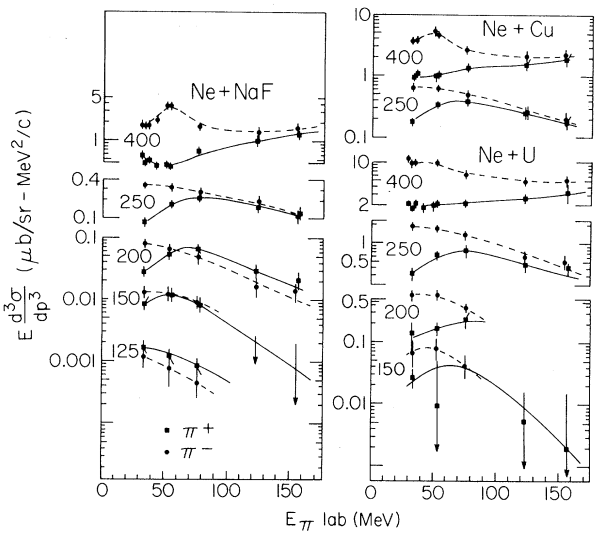

FIG. 2. The invariant cross section vs pion energy at 0° for various targets and Ne beam energies (in MeV/nucleon).

In 1977 a report was given of some anomalously large pion-production cross sections measured in emulsions with beam energies from 100-280 MeV/nucleon.[9] These measurements were later refuted by two other experiments[10,11] which saw no pions at all, and indicated that emulsion techniques did not have the sensitivity necessary for such small cross sections.

The present measurements were made with Ne (from 125 to 400 MeV/nucleon) produced by the Bevalac at the Lawrence Berkeley Laboratory. The targets of NaF, Cu, and U were 10 cm by 10 cm in size and 1–2 g/cm^2 thick, and the beam spot was about 1 cm in diameter on target. NaF was chosen as the solid target in which the nucleon-nucleon and nucleus-nucleus frames were as close to coincident as possible. Gas targets are not feasible for this experiment since they cannot provide an adequate number of atoms per square centimeter. Theories of the process are insensitive to nuclear structure differences between Na, Ne, and F in any case. The 180° magnetic spectrometer was constructed from a large, flat-field, dipole magnet. The target, spectrometer, and detectors were in air, with the beam exiting from vacuum about 2 m before the target. Pion yields at three different momenta were measured at each spectrometer field setting. The momenta were defined by lead collimator slits placed on the focal plane of the spectrometer, and the pions were detected by independent four-element plastic scintillator telescopes placed behind each slit. The integrated beam intensity was determined with an ion chamber which was calibrated by individual particle counting at reduced beam intensities and by induced ^{14}C activity. The data were corrected for π decay in flight, absorption in the air, scintillators and absorbers, and multiple scattering.

Because the collimators narrowly limited the momentum range of particles reaching the telescopes, pions were the only particle type which could make a triple coincidence without triggering an anticoincidence from the back elements. That the particle group stopping in the third scintillator was, in fact, pions was verified for π^+ by observing their total energy loss and the μ^+ decay lifetime. The negative pions were characterized by the large range of pulse heights in the third scintillator which was due to stars from nuclear capture. To ensure an equal efficiency for π^+ and π^-, only the energy loss in the first two detectors and the requirements of any signal in the third and no signal in the fourth element were used to define an event.

A complete set of 0° data is given in Fig. 2. Angular distributions were also measured in 7.5° steps between 0° and 30° at 250 MeV/nucleon on NaF and U targets. They are quite isotropic, and the magnitudes of the cross sections and the pion energy distributions are in very good agreement with existing data at nearby angles.[5,6] The target-mass dependence of the data is approximately $A^{2/3}$ but differs somewhat at the lower pion energies. The absolute cross sections indicated in Fig. 2 are believed accurate within a factor of 2 at present, with the error bars indicating all statistical and relative-cross-section uncertainties. Relative π^+ and π^- cross sections are better determined because several uncertainties cancel in the ratio.

The ratio, R, of the π^- to π^+ cross sections is plotted in Fig. 1 for the Ne + NaF data at 0° for all five beam energies studied. The ratios are plotted as a function of the pion kinetic energy relative to the projectile. There is an unexpectedly large and narrow peak in the 400-MeV/nucleon data. For the 250-MeV/nucleon data the lowest pion energy point recorded in the laboratory (34 MeV) corresponds very nearly to zero energy in the projectile system, and there is a large ratio at this point also. There is also a tendency towards a peak in the 200-MeV/nucleon data, but for the two lowest-beam-energies data were not recorded at low enough pion energies.

A large fraction of the pions created with zero kinetic energy in the projectile frame probably results from peripheral collisions. In this case the peak observed in the π^-/π^+ ratio can be qualitatively explained in terms of Coulomb distortion of the pion wave functions in the vicinity of the projectile charge. The Coulomb wave for the π^- is enhanced near the positive charge of the nucleus, while that of the π^+ is reduced. A calculation using a charge and radius appropriate for the projectile ignoring the Coulomb effects of the target yields the solid curve in Fig. 1.

While this mechanism appears to offer a feasible qualitative explanation of the peak, a more precise treatment will be necessary to explain it in detail. More complete pion spectra at the lower beam energies, at additional higher beam energies, as well as with other beam-target systems are necessary to develop a real understanding of this structure. Furthermore, there is presumably a similar, but less well defined Coulomb effect for pions created at rest in the center-of-mass system by central collisions. The heights, widths, and positions of these Coulomb phenomena may yield valuable information on the relative amounts of central and peripheral collisions, as well as being sensitive to the microscopic details of the spatial size and time scale of the interaction.

Other features of the data which we would like to mention here are the absolute pion-production cross sections and the rapid rate of decrease of the yields with decreasing beam energy. The original purpose of this experiment was to look for deviations from the predictions of a simple Fermi-gas production mechanism[12] at the lowest possible beam energies. Reference 12 was modified to account better for the isobar dynamics in pion creation and to include momentum-dependent absorption of the pions after creation. The lower dashed curve in Fig. 3 shows that this model can account for the absolute pion yields at the lowest beam energy, at least within a factor of 2. Figure 3 also shows, however, that this model seriously underestimates the production cross sections, by nearly an order of magnitude, at 200 MeV/nucleon. In other words, the rapid rate of increase of pion yield with beam energy indicates that the single-first-collision Fermi-gas picture

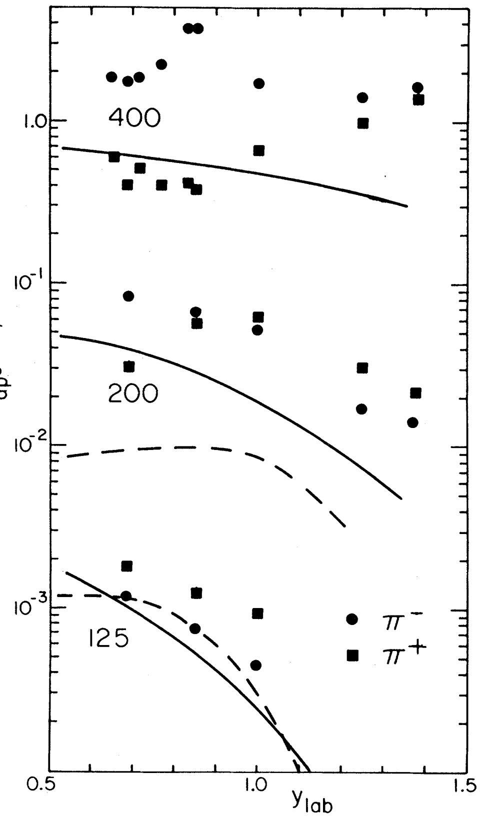

FIG. 3. Pion production cross sections for Ne + NaF (0°) as a function of pion rapidity, $y = \frac{1}{2}\ln[(1+\beta)/(1-\beta)]$. The solid lines are the prediction of the thermal model at the three energies, and the dashed lines are the prediction of the first-chance collision model at 125 and 200 MeV/nucleon. At 400 MeV/nucleon it underpredicts the cross section by too much to make a meaningful comparison.

is inadequate except at the lowest energies of the "subthreshold" region.

An additional production mechanism must be involved to account for the large production cross sections at the higher beam energies studied here. The predictions of a thermal fireball model[13-15] are shown as solid curves in Fig. 3. In this model, pions are statistically evaporated from a region of hot nuclear matter consisting of those nucleons which were in the region of overlap during the nuclear collision. As shown, this model can nearly account for the pion yields at 200 MeV/nucleon and above, just where the Fermi-gas model fails.

In conclusion, data on pion production in heavy-ion collisions covering a new kinematic regime have been presented. A sharp peak in the relative π^- to π^+ yields at the projectile velocity has been observed. This peak is unrelated to the π^+ enhancement seen at 90° with higher beam energies.[5,6,16] Further detailed theoretical and experimental studies of the new peak may yield valuable information about the microscopic structure of the heavy-ion interaction region. The rapid rate of change of pion yield with beam energy is inconsistent with the first-collision Fermi-gas production model, but the absolute predictions of this model are approximately correct at the lowest energy studied here (125 MeV/nucleon). More detailed application of the thermal-production mechanism to these data and other pion-production data is necessary before any conclusion on the absence or presence of new collective phenomena can be made.

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