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SUBTHRESHOLD NEGATIVE PIONS AND ENERGETIC PROTONS PRODUCED AT $\theta_{cm} = 90°$ IN 246 MeV / nucleon ^{139}La + ^{139}La COLLISIONS

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The inclusive cross section for subthreshold negative pions and high energy protons produced at $\theta_{cm} = 90°$ has been measured for ^{139}La + ^{139}La at 246 MeV/nucleon. The spectrum of negative pions exhibits no bump or sharp break as has been suggested by theoretical speculation on the formation of a pionic instability in central nucleus–nucleus collisions. The measured spectra for both pions and protons are compared with results of a phase space model and an intranuclear cascade calculation.

The primary motivation for this experiment was to test the theoretical speculation [1] that a pionic instability could be created when large nuclear systems collide centrally. The signature suggested for this new phase was an increase in the number of pions produced at $\theta_{cm} = 90°$ with momenta centered around $\sim(2\text{–}3)m_{\pi}c$. A similar study [2] of the inclusive negative pion distribution has previously been made at an incident energy of 183 MeV/nucleon for the light Ne + NaF system. In that study, the pion spectrum at $\theta_{cm} = 90°$ was found to fall smoothly as a function of the pion's center-of-mass kinetic energy, with no hint of any localized increase in yield. However, theoretical considerations stress the importance of using heavy projectiles and targets to involve the largest amount of participant matter and thereby enhance the possibility of producing the new phase [1]. For this reason, we have chosen the La + La system to search for the proposed effect. The spectrum of energetic protons produced at $\theta_{cm} = 90°$ was also measured to provide an estimate of the "temperature" achieved in these collisions.

This experiment was carried out on one arm of the two-armed spectrometer system (TASS) [3] at the Bevalac. The ^{139}La beam with a charge state of +29

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and an energy of 255 MeV/nucleon was focused onto a 408 mg/cm^2 La target, with maximum beam intensities of (2–3) × 10^7 per pulse recorded by a calibrated ion chamber. After accounting for energy loss due to ionization in the target we estimate the mean beam energy at the center of the target to be 246 ± 1 MeV/nucleon. The incident energy and the target thickness were chosen as a compromise between the small pion cross sections expected, the rapid decrease of these cross sections with reduced incident energy, the large energy loss in the target experienced by high-Z projectiles, the maximum achievable beam intensity, and, finally, our desire to suppress incoherent pion production such as $\mathrm{NN} \to \mathrm{N}\Delta \to \mathrm{NN}\pi$. The data have been corrected for energy loss, nuclear absorption in the target and other material in the spectrometer, and for pion decay in flight. We estimate the overall uncertainty in the absolute value of the cross sections to be 25%.

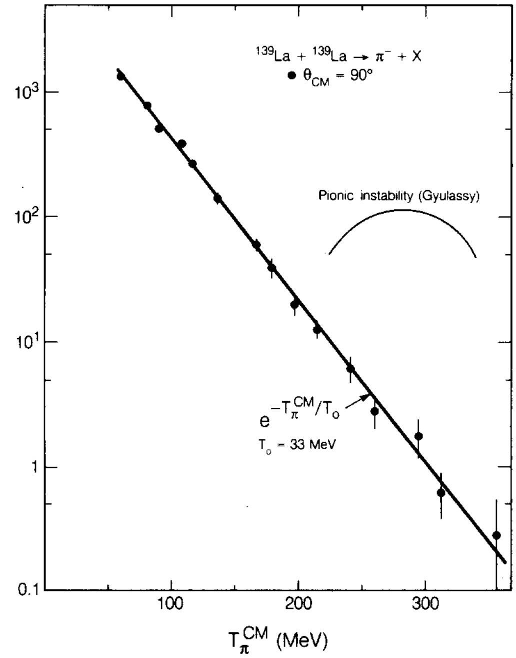

Fig. 1. Lorentz invariant cross section for negative pions produced at $\theta_{\mathrm{cm}} = 90°$ in La + La collisions at 246 MeV/nucleon as a function of the pion's center-of-mass kinetic energy. The $\theta_{\mathrm{cm}} = 90°$ data have been fit to the form $E\,\mathrm{d}\sigma/\mathrm{d}p^3 \propto \exp(-T/T_0)$. The theoretical prediction for the pionic instability (ref. [1]) is shown as a solid curve.

Fig. 1 displays the measured Lorentz invariant cross section, $E\,\mathrm{d}\sigma/\mathrm{d}p^3$, for inclusive production of negative pions at $\theta_{\mathrm{cm}} = 90°$. Several features are evident. First, the measured pion cross sections fall exponentially over almost four orders of magnitude in cross section with a slope parameter, $T_0 = 33$ MeV. There is no evidence for either a bump or break in the distribution which would indicate the presence of an exotic nuclear phase, such as a pionic instability. Using Gyulassy's estimate [1] indicated by the solid curve in fig. 1, we estimate an upper limit on the production of a pionic instability in ^{139}La + ^{139}La collisions at 246 MeV/nucleon of about 1% of the measured inclusive cross section.

A second prominent feature of the pion data shown in fig. 1 is that the cross sections remain measurable even at pion energies as large as 360 MeV. This calls into question several of the nuclear mechanism(s) which have been proposed for the production of energetic pions. The simplest mechanism is that of pion production via a single nucleon–nucleon collision with the proper inclusion of Fermi momenta. However, a simple calculation shows that such a model is not able to explain the high energy portion of the spectrum because Fermi momenta in excess of 600 MeV/c in both target and projectile nuclei would be required to produce the highest energy pions observed in this experiment. On the other hand, if one invokes a multiple-scattering approach, then over eight nucleons, each having the initial center-of-mass kinetic energy of 62 MeV/nucleon, would be required to give up all of their energy to create (rest mass + kinetic energy) a 360 MeV pion. This suggests some type of cooperative nuclear phenomena must be involved in the creation of the highest energy pions in these collisions.

The inclusive distributions ($\mathrm{d}\sigma/\mathrm{d}p^3$) for negative pions and protons produced at $\theta_{\mathrm{cm}} = 90°$ are compared in fig. 2. In order to gain more insight into the dynamics of the collision process, we have compared our data with a phase space and an intranuclear cascade model.

We first consider the predictions of a phase-space model [4,5]. In this model the collision process is divided into a sequence of interactions between nucleons within tubes. In turn, using Glauber theory [6], the number of nucleons in each tube is determined by the sizes of the nuclei and the impact parameter.

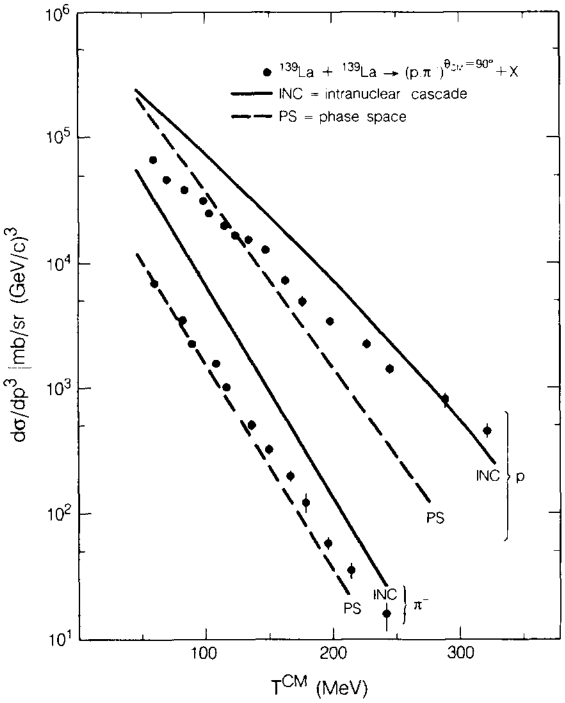

Fig. 2. The variant cross section ($d\sigma/dp^3$) for θ_{cm} = 90° negative pions and protons as a function of center-of-mass kinetic energy. Dashed lines represent the predictions of a phase-space (PS) model, and the solid lines represent the predictions of an intranuclear nuclear cascade (INC) calculation.

Once the number of nucleons is determined, the emission of particles is strictly governed by phase-space considerations [7]. For a given impact parameter the contributions from each of these tube–tube collisions are added incoherently to obtain the emission of final-state particles. Results of this model for the conditions of our experiment are shown as the dashed lines (PS) in fig. 2 [8]. The prediction of the model for pions has the same general shape as the data, but slightly underestimates the negative pion cross section. Part of this underestimate is due to the fact that the model does not properly take into account isospin of the pions [5,8]. For protons the phase-space model suggests a much more rapid fall-off with proton kinetic energy than is observed.

Next we compare the measured yields of negative pions and protons with the predictions of an intranuclear cascade model [9]. This model assumes that the collision can be broken up into individual nucleon–nucleon encounters with the proper inclusion of Fermi momenta. Approximately 60 000 events were generated at 246 MeV/nucleon with a maximum impact parameter of b_{max} = 11.6 fm to obtain the distributions shown in fig. 2. The normalization comes from assuming a total cross section given by the geometric limit, πb^2_{max}. The solid lines (INC) shown in fig. 2 represent free-hand curves through the cascade generated distributions. The negative pion yield was obtained by taking into account properly the isospin of the target and projectile. The general fall-off of the cross section for both pions and protons is reproduced by the calculation. But in both cases the yields are overestimated at energies below 250 MeV.

Within the framework of the intranuclear cascade model we are able to extract additional information on the collision process. Two quantities which can be easily calculated are the average values of the impact parameter $\langle b \rangle$ and the number of participating nucleons $\langle n_{part} \rangle$. Integrating over the measured energy range of produced particles we obtain for the cascade generated events an average impact parameter of $\langle b_\pi \rangle = 4.6 \pm 0.2$ fm for pions and $\langle b_p \rangle = 4.8 \pm 0.1$ fm for protons emitted at θ_{cm} = 90°. For comparison, the average impact parameter for events integrated over all angles and energies was found to be $\langle b \rangle_{all}$ = 7.7 fm. Thus within the framework of the model, particle production at θ_{cm} = 90° and kinetic energies > 60 MeV, imply that a relatively central collision has occurred, with an average of $\langle n_{part} \rangle \sim$ 130–150 nucleons being involved in an event. Furthermore we find from the model that increasing the energy of the particle observed at θ_{cm} = 90° does not substantially reduce the average value of the impact parameter or significantly increase the number of participating nucleons.

Inclusive distributions for particle production at θ_{cm} = 90° have traditionally been used to estimate the temperature of the emitting source [10]. The procedure involves fitting the Lorentz invariant cross section to the form, $E\, d\sigma/dp^3 \propto \exp(-T/T_0)$; where T is the center-of-mass kinetic energy of the produced particle, and T_0 is the inverse slope parameter, which has frequently been interpreted as the "temperature" of the source. To be more rigorous, one should actually fit the exponential to the variant cross section, $d\sigma/dp^3$. However, in order to compare our results with previous experiments we have followed the procedure

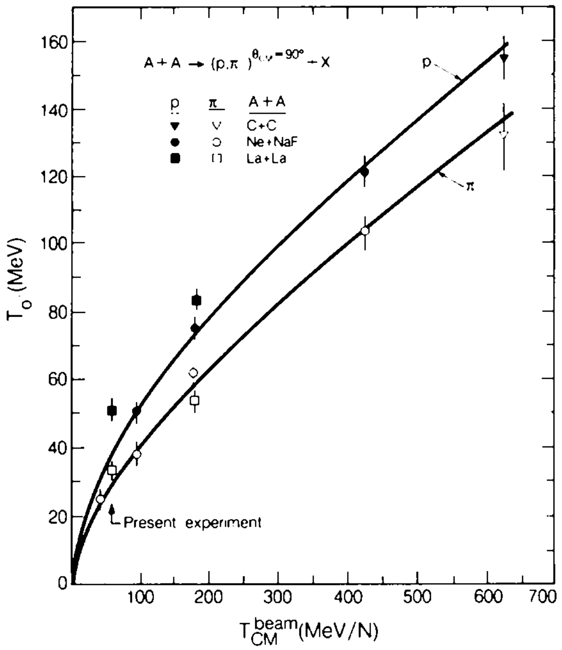

Fig. 3. Energy and target–projectile mass dependence of the inverse slope parameter, T_0. In all cases, T_0 obtained from fitting Lorentz invariant cross sections at $\theta_{cm} = 90°$ to the form $E\mathrm{d}\sigma/\mathrm{d}p^3 \propto \exp(-T/T_0)$.

of fitting to the invariant forms. We find that the measured distributions for negative pions and protons correspond to temperatures of 33 ± 4 MeV and 51 ± 4 MeV, respectively. Fig. 3 shows the inverse slope parameter T_0 versus the center-of-mass kinetic energy/nucleon (T_{cm}) of the projectile. Data for a variety of equal-mass projectile–target combinations is shown [11–13]. The solid curve is a free-hand curve through the Ne + NaF data to provide a guide to the eye. The value for the inverse slope parameter increases with bombarding energy with the apparent temperature of the proton source being greater than that for pions. A recent study [14] of central Ar + KCl collisions at 1.8 GeV/nucleon is consistent with this feature, and attributes this difference to the kinematics of the decay of produced Δ's.

In summary, we have studied the production of subthreshold negative pions and energetic protons at $\theta_{cm} = 90°$ in ^{139}La + ^{139}La collisions at 246 MeV/nucleon. No bump or break in the inclusive pion spectrum is observed, arguing against the strong formation of a pionic instability. Intranuclear cascade calculations provide a better overall representation of the shapes of the negative pion and proton energy distributions than do results of a phase-space model.

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