Cooperative Effects Observed in the π^0 Production from Nucleus-Nucleus Collisions

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Cooperative effects in collisions of 60–84-MeV/u ^{12}C projectiles with different target nuclei have been experimentally established through π^0 production, especially through the measurement of the apparent velocity of the pion source. Our method for the spectroscopy of neutral pions covers all angles and kinetic energies (down to zero). The exponential slopes in the spectra contain rather high Fourier components indicating the presence of short-distance phenomena in the collision dynamics.

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Nucleus-nucleus collisions at energies high above the Coulomb barrier have attracted much attention as a possible means to study highly excited nuclear matter far from ground-state conditions. A necessary requirement for such formation of excited nuclear matter is the transformation of energy from the relative motion during the collision. To study the properties of the internuclear collision zone, nonnucleonic probes like mesons seem to be a very good choice,[1,2] since they are likely to be produced by the participant parts of the colliding nuclei alone. This is in contrast to the observation of nucleons, for example, whose spectra[2] also show large components from the target and projectile rapidity regions. Neutral mesons as probes have the additional advantage that the kinematic information they carry is not hampered by deflection in the Coulomb field of the collision fragments.[1] In this Letter we present results of a study of nucleus-nucleus collisions at projectile energies of 60–84-MeV/u through the accompanying π^0 emission. Especially we want to show that the apparent source of the pions behaves much different from what is expected from *N-N* collisions, indicating that the pion production is not just due to single collisions between nucleons which have received an extra boost from the intrinsic Fermi motion[3] in the two nuclei. A cooperative production mechanism involving a coherent interaction of many nucleons from the two collisions partners is therefore required, thus opening interesting aspects for the investigation of the collision dynamics.

The large detection efficiency needed for a detailed investigation of the rather small pion-production cross sections was obtained by employing the prompt decay of π^0's into two γ rays. We used a detector consisting of two concentric rings of lead-glass Cherenkov counters; details of the instrument and its properties will be published[4] elsewhere. It should be pointed out, however, that for pions from 0 to 400 MeV kinetic energy the full angular range was covered with a rather high efficiency of more than 1% (known with 9% accuarcy due to threshold effects). Most background radiation could be suppressed very effectively by requiring the two gamma rays to yield the proper invariant mass of 135 MeV; the remaining background was shown to account for less than 30 pb/MeV (after a proper subtraction of cosmic-ray events as accumulated with the beam off). The measurements were performed at the CERN synchrocyclotron using ^{12}C ions of 84 MeV/u; degrader foils were used to obtain also 74- and 60-MeV/u ions. Data were taken with integral beam particle doses of about 10^4 for each of the projectile-energy–target combinations studied and targets of 50–90 mg/cm^2 thickness. Beam integration and target thickness contribute 7% and 5%, respectively, to the systematic error on the absolute cross sections.

The angular dependence of the inclusive π^0 production cross section with ^{12}C projectiles of 84 MeV/u is displayed in Fig. 1. There the pion emission into the full phase space is shown as a contour plot of the invariant cross section. As they should be, the data for the $^{12}C + ^{12}C$ collision system are forward-backward symmetric about 90° in the c.m. system. Requiring a forward-backward symmetry also for asymmetric systems enables one to determine the mean rapidity of the source emitting the pions. This is demonstrated for ^{12}C on ^{238}U in the

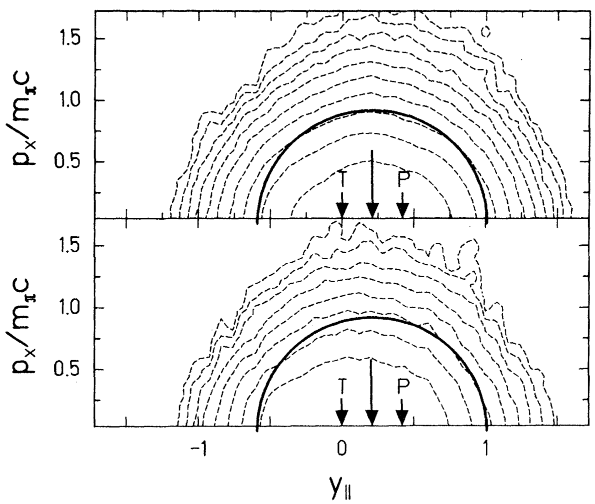

FIG. 1. Invariant pion emission cross section $d\sigma/p\,d\Omega\,dE$ vs rapidity y and perpendicular momentum p_x for the systems $^{12}C+^{12}C$ (top) and $^{12}C+^{238}U$. The cross section rises by a factor of 2 between subsequent contour lines; the arrows on the abscissa depict the rapidity of target (T) and of projectile (P) and their mean. The drawn line corresponds to an isotropic emission of pions ($p_\pi = 100$ MeV/c) from the midrapidity system, which is representative for a production from *N-N* collisions.

lower part of Fig. 1, where obviously the center of the contours observed is shifted considerably as compared to that for ^{12}C on ^{12}C. This is characteristic for the emission from a much slower source and is in strong disagreement with charged-pion production data[2] taken at 183 MeV/u and higher energies, where the angular distributions for symmetric as well as asymmetric systems are centered (i.e., forward-backward symmetric) about a point at $\simeq 50\%$ of the beam rapidity, indicating the dominance of pion production from *N-N* collisions. On the contrary, in our case, the pions are obviously produced cooperatively through the interaction of the projectile with a large portion of the target nucleus acting as a whole.

To quantify this effect we list in Table I for several collision systems the information on the average rapidity of the source emitting the pions, determined from the centroid of invariant distributions as shown in Fig. 1. We note that in this averaging the abundant low-momentum pions are the most important. Their large wavelength together with their large mean free path[5] reduces the importance of absorption and rescattering effects which in principle could distort the pion distributions. The experimentally determined rapidity for the Ni and U targets falls in between the value for $^{12}C+^{12}C$, which is representative for the *N-N* case, and the calculated rapidity of the center of mass of the colliding nuclei. Through simple kinematical relations the experimental rapidity yields the apparent mass of the collision partner with which the ^{12}C projectile interacts in the heavy target nucleus. A best fit to the data taken at the three beam energies results in a value of 23 mass units for the Ni target (33 for U), quantitatively indicating the collectivity of the pion production process observed. The integrated cross sections for the different systems are also listed in Table I. They are of about the same size as charged-pion data[6] taken at similar bombarding energies and are well described by a

TABLE I. Parameters characterizing the observed pion production from three collision systems at three beam energies. For each combination is listed (a) the angle- and energy-integrated cross section; (b) the rapidity of the source emitting the pions averaged over their spectrum; (c) the rapidity calculated for the nucleus-nucleus c.m. system; (d) the parameters of the exponential slope; and (e) the slowing-down length calculated from the slope parameters.

A_1	A_2	E/A (MeV/u)	(a) σ (μb)	(b) $y_{\rm exp}$	(c) $y_{\rm c.m.}$	(d) E_0 (MeV)	(e) γ (fm)
C	C	84	18.9(23)	0.20(1)	0.21	28(2)	1.4(2)
		74	8.5(10)	0.21(1)	0.20	25(2)	1.5(2)
		60	1.7(3)	0.18(1)	0.18	22(2)	1.5(2)
C	Ni	84	72(9)	0.16(1)	0.08	27(2)	1.5(2)
		74	31(4)	0.14(1)	0.07	27(2)	1.4(2)
		60	7(1)	0.12(1)	0.06	22(2)	1.6(2)
C	U	84	174(21)	0.11(1)	0.02	26(2)	1.5(2)
		74	64(10)	0.10(1)	0.02	26(2)	1.5(2)
		60	13(2)	0.09(1)	0.02	15(3)	2.2(5)

$(A_1A_2)^x$ dependence with $x \sim 0.65$; between 60 and 84 MeV/u they increase by more than a factor of 10. Angle-integrated π^0 spectra as shown in Fig. 2 are characterized by a peak at around 20 MeV kinetic energy and an exponential decrease, which reaches to rather high energy. In Table I we have included the slope parameters E_0 of these exponential tails as deduced in the laboratory frame; an estimate for the systematic error on E_0 was obtained from a Monte Carlo simulation[4] of our detector accounting for its limited gamma-ray resolution. The value for E_0 increases with increasing beam energy, and the slopes observed for different target masses at the same beam energy are surprisingly constant.

Different methods have been proposed for the solution of the complicated quantal many-body problem of two fast nuclei colliding with each other. One type of model makes use of phase-space arguments[7] and relies on the assumption of statistical equilibrium in the collision zone. The application of such an approach to charged-pion production at 86 MeV/u revealed[8] a considerable freezing of degrees of freedom as compared to the assumption of free nucleons and thus gives a measure of the collectivity of the process. The dynamical aspect of the collision comes out more clearly in those models which consider the pions to be emitted in a radiative process analogous to the emission of γ quanta from a moving charge and thus to reflect the properties of the collision zone and its evolution in space and time. Such an inherently cooperative picture evolves from the observation[9] that exponential slopes in radiation spectra do not necessarily indicate a thermal emission but can also be due to emission from an accelerated or decelerated source. We note that for a pointlike source, straight-line trajectories, and a Lorentzian slowing-down function with width 2τ full width at half maximum (FWHM), the bremsstrahlung spectrum[10] as given by the Fourier transform of the deceleration is an exponential in E with a slope $E_0 = \hbar/2\tau$ (for $E > E_0$), when averaged over possible directional effects as we do with our angle-integrated data. Analogous to the electromagnetic bremsstrahlung we applied this formula to the observed pion spectra although in principle the observed slopes in the spectra are governed by the spatial properties[11] of the pion source as well as by its time derivative.[12] But when we deduce a characteristic time τ from the experimentally determined slope parameters, we observe that the values for E_0 and τ vary considerably with the bombarding conditions whereas the slowing-down length $\lambda = c\beta_i\tau$ is remarkably constant over the range covered by this experiment. This indicates this length, over which the relative motion of the two nuclei (characterized by the initial velocity β_i) is slowed down, to be the characteristic parameter for such an analysis. Nearly the same slowing-down parameters were obtained from a fit of a more general "pionic bremsstrahlung" formalism[13] to some of our data, which also reproduces the measured absolute cross sections reasonably well; the small probability for pion production is due to its assumed radiative character. *N-N* contributions to the pion production which are likely to disturb the picture severely have been shown[8] to be negligible at these energies.

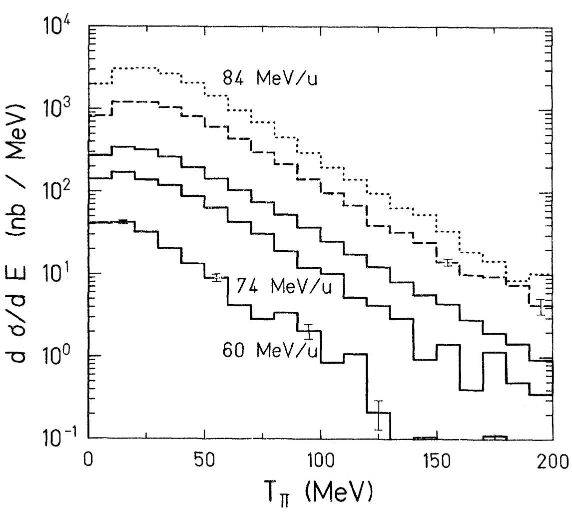

FIG. 2. Pion kinetic energy spectra for the $^{12}C + ^{12}C$ system as measured at 60, 74, and 84 MeV/u (solid lines) and for $^{12}C + ^{56}Ni$ and $^{12}C + ^{238}U$ at 84 MeV/u (dashed and dotted lines, respectively).

To conclude: Cooperative effects in the pion production from collisions of 60–84 MeV/u ^{12}C projectiles with targets from $A = 12$ to $A = 238$ have been established. The picture of pion production caused by a collective deceleration of the projectile as applied to our data allows the extraction of characteristic deceleration times or lengths. These slowing-down lengths are rather short (~ 1.5 fm) and surprisingly independent of beam energy and target mass thus justifying *a posteriori* the parametrization with this quantity. At projectile energies of around 70 MeV/u violent nucleus-nucleus collisions are hence observed where a large amount of energy is taken our of the relative motion by slowing down the collision partners over a rather short distance. It seems intriguing to investigate such a nuclear stopping process also through the observation of electromagnetic bremsstrahlung[4, 13] or, especially at higher energies, through the production of heavier mesons.

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