Subthreshold Pion Production in Heavy-Ion Collisions at 85*A* MeV

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The π^+ production in 85*A*-MeV C + C and C + Au reactions has been studied for 20 MeV $\leq E_\pi \leq$ 80 MeV and $\theta_{\rm lab} > 55°$. The cross sections, $d^2\sigma/d\Omega\, dE$, fall exponentially with E_π and are 9 times larger for C + Au than for C + C. The angular distribution is backward peaked for C + Au in the nucleon-nucleon c.m. system, while it is weakly forward peaked in the nucleus-nucleus c.m. system. An independent nucleon-nucleon scattering model can explain the data only if diffuse internal momentum distributions are introduced.

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The availability of heavy-ion accelerators in the intermediate energy region has opened up new possibilities to study pion production at an energy per nucleon below the free nucleon-nucleon threshold (290 MeV). Hadron-nucleus collisions[1,2] have been used for many years to examine the importance of the nuclear environment in the pion production process. Very large momentum transfers to the nucleus (2–3 times the Fermi momentum) can be involved in these reactions, a fact which points towards a large degree of coherence. However, the reaction mechanism is not convincingly explained. Nucleus-nucleus reactions substantially below the free threshold have been studied only in the experiments of Benenson *et al.* A pronounced minimum in the π^+/π^- ratio has been observed for velocities (or rapidities) close to that of the projectile.[4] This phenomenon has been explained in terms of Coulomb effects.[5] Fully coherent production in light-ion reactions, like $^3He + ^3He \rightarrow ^6Li + \pi^+$, has been observed with cross sections of the order of 100 nb at energies (90*A* MeV) close to the reaction threshold.[6] At higher energies (303*A* MeV) such coherent channels are much less important.[7] Subthreshold pion production in heavy-ion interactions could be explained in various ways. The most obvious way is to produce pions via nucleon-nucleon collisions, taking into account the boost from the internal (Fermi) momenta.[8,9] Collective phenomena such as collisions between clusters[10,11] or the coherent production of an isobar[12,13] are other possibilities. More exotic phenomena, such as pion condensation[14,15] appearing in dense regions of the ion-ion system, have also been discussed. In this Letter, we report on the results of an inclusive study of the π^+ production at large angles, using a ^{12}C beam with an energy of $(85 \pm 1)A$ MeV.

The ^{12}C beam from the CERN synchrocyclotron, with intensities between 2×10^9 and 2.5×10^{10} ions/s, impinged on a carbon or gold target. The target thicknesses were 51 and 38 mg/cm^2, resulting in small energy losses and thus a very well defined effective beam energy of $(85^{+1}_{-2})A$ MeV.

The range telescope, used to detect pions, was designed to be sensitive to cross sections of about 0.1 μb/sr. It consisted of six plastic scintillators (5, 25, 50, 50, 50, and 5 mm thick). The first element was used only as a ΔE detector and the last element only as a veto detector. An 8-mm plastic absorber was necessary to reduce the intense proton flux especially at 55° and it increases the effective pion-energy cutoff to 17 MeV. The trigger for a positive pion was a delayed (within 200 ns) signal $(\pi^+ \rightarrow \mu^+ + \nu_\mu)$ from the stop (st) detector following any $s_1 * \cdots * s_{st} * \bar{s}_{st+1} * \cdots * \bar{s}_6$ coincidence. All ΔE-ΔE correlations were further used for the identification. The time spectra and the (monoenergetic) signal from the decay muon were recorded. Prompt runs (i.e., with no delayed coincidence requirement) were made throughout the data-taking period in order to check the stability of the system. The dead-time due to the prompt pulse length reduces the pion registration efficiency in the stop detectors to between 25% and 35%. Since no deviation from a constant background was found, the total π^+ yield was obtained by fitting the function $A + B\exp(t/\tau)$, $\tau = 26.02$ ns, to the time spectra.

Each scintillator constitutes one energy bin, obtained from the range-energy relation. The error bars in Fig. 1 are mainly due to statistical errors in the χ^2 fit procedure but the uncertainty in the zero time determination has also been included. In calculating the cross sections, we have corrected for decay in flight (15%–17%) and nuclear collisions before the stopping point (10%–20%). The multiple Coulomb scattering correction (see Chiba[16]), as well as the correction due to loss of muons and pions from the finite geometry, is negligible. A three-element plastic-scintillator telescope served as a monitor. The errors in the absolute cross section of π^+, mainly due to the uncertainty in the beam current measurement with a Faraday cup[17] and the effective solid angle determination, add up to about 30%. The prompt $d^2\sigma/d\Omega\, dE$ spectra of protons at 90° are, within this uncertainty, in agreement with those found in Ref. 17.

The $d^2\sigma/d\Omega\, dE$ spectra of π^+ in Fig. 1 show an exponential falloff with energy in the interval $20 \leq E_\pi \leq 80$ MeV, with a slope which becomes slightly steeper with increasing laboratory angle. The shapes of the spectra are similar for C and Au targets. The cross section for C + Au collisions is 9 times larger than that for C + C collisions. Under the assumption that the cross sections follow an A^α power law, α would be 0.8. The integrated cross section $\int (d^2\sigma/d\Omega\, dE) dE$ for C + C is 0.8 μ/sr at 55°, 0.5 μb/sr at 90°, and 0.4 μb/sr at 130° to be compared with about 10

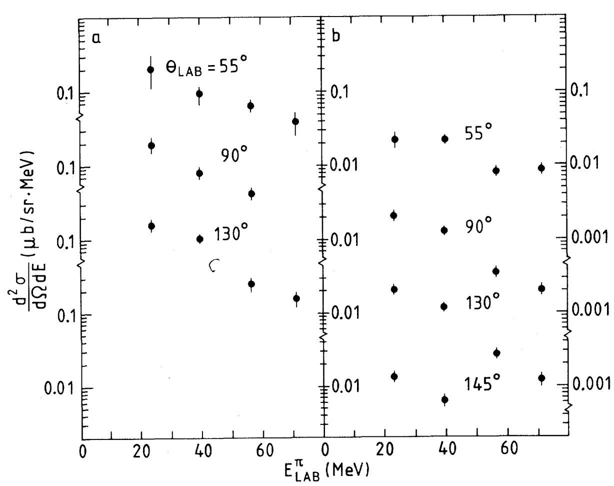

FIG. 1. Doubly differential cross sections of π^+ from (a) C + Au and (b) C + C collisions at 85*A* MeV as a function of the pion kinetic energy.

μb/sr at 0° for Ne + NaF in the experiment of Benenson *et al.*[3] If the comparatively weak slope in the angular distribution, which we find, is valid also for $\theta < 55°$ (a fairly uniform $d\sigma/d\Omega$ distribution for $\theta < 30°$ is reported in Ref. 3) and the cross section is proportional to $A_1^{0.8}A_2^{0.8}$, then our cross sections are slightly smaller than those in Ref. 3. However, the effective beam energy in Ref. 3 is reported with a large error, $(80 \pm 10)A$ MeV, and it is possible that the π^+ production cross section is falling more steeply with decreasing beam energy than was assumed there. An extrapolation to 180° of the angular distribution for C + C reactions in Fig. 2(a) results in a total π^+ production cross section of ~10 μb.

In Figs. 2(a)–2(c) the invariant cross section $(1/p)d^2\sigma/d\Omega\,dE$ is plotted against the emission angle in the nucleon-nucleon c.m. frame, in the nucleus-nucleus c.m. frame, and in the laboratory frame. The C + C cross section is found to be symmetric in Figs. 2(a) and 2(b) as it should be in any c.m. system. The C + Au spectrum of π^+ is, however, strongly backward peaked in the nucleon-nucleon c.m. frame ($\beta_{\text{c.m.}} \simeq 0.20$). On the other hand it seems [Fig. 2(b)] to be slightly forward peaked in the nucleus-nucleus c.m. frame ($\beta_{\text{c.m.}} \simeq 0.023$). This might indicate the presence of mechanisms involving more than two independent nucleons, such as collisions between clusters or the creation of a locally heated, dense subvolume of nuclear matter ($\langle\beta_{\text{FB}}\rangle \simeq 0.13$ in the clean-cut fireball approximation). One should, however, bear in mind that pions created, for instance, in independent nucleon-nucleon collisions are reabsorbed when traversing the remaining parts of the nuclei and that an asymmetry could be created in this way.

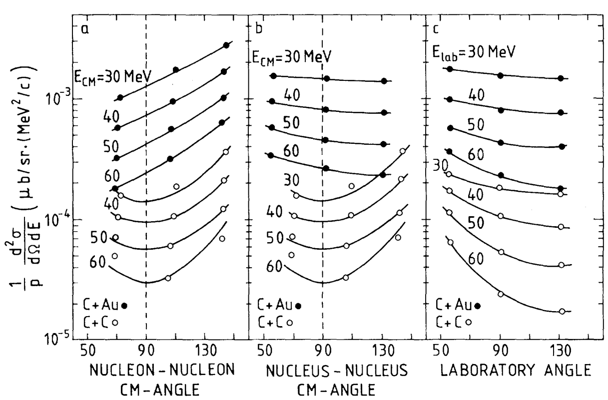

FIG. 2. Lorentz-invariant doubly differential cross sections as a function of (a) the nucleon-nucleon c.m. angle, (b) the nucleus-nucleus c.m. angle, and (c) the laboratory angle. The curves are drawn to guide the eye. In the c.m. spectra for C + C we have chosen to draw them symmetric around 90°, thereby presenting typical errors in the individual points.

The apparent temperatures of the pion-producing sources obtained from fits of Lorentz-transformed relativistic Boltzmann-like sources to the spectra of Fig. 1 (Ref. 17) are 14 ± 1 MeV for C + C collisions and 15 ± 1 MeV for C + Au collisions. The latter one is, within the limits of error, the same as the Boltzmann temperature for high-energy protons given in Ref. 17, while the temperature for pions in C + C events is even slightly higher than that for protons. It should be noticed that smaller apparent temperatures for pions than for protons have been observed at higher beam energies,[18] a phenomenon which is explained in the framework of an expanding common Boltzmann-like source.[19] Preliminary calculations of the π^+ production cross section in C + C collisions with an independent nucleon-nucleon scattering model have been performed.[20] From these calculations we have observed that the absolute cross section (especially for pions with $E_\pi > 60$ MeV) can be reproduced only if diffused internal momentum distributions (e.g., of harmonic-oscillator type for light nuclei) are introduced. The largest contribution to the π^+ production is coming from the $pp \to d\pi^+$ channel since the Pauli blocking in this case (two nucleons with the same final momentum) is weaker than for (two nucleons) + π^+ in the final state.

In conclusion, we have obtained π^+ production cross sections at 85A MeV with an A dependence close to $A^{0.8}$. The apparent production source has a velocity between the nucleon-nucleon c.m. velocity and the nucleus-nucleus c.m. velocity. The absolute cross sections could possibly be explained in the framework of independent nucleon-nucleon collisions from two interacting momentum spheres but only if we assume a strong $pp \to d\pi^+$ component for which Pauli blocking could be treated as if two nucleons with the same final momenta are produced.

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Interference Effects in Molecular Autoionization Realized by Li^+ + He Collisons

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Measurements have been made of spectra of electrons resulting from autoionization of a doubly excited quasimolecular state in a Li^+-He collision. An isolated peak is observed beyond the classically accessible energy region of the backward electron emission. The occurrence of this peak is interpreted as due to a new type of interference among the probability amplitudes of the ejected electrons.

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Yagishita and co-workers[1,2] have investigated collisionally excited autoionization states in the Li^+-He system by means of ejected-electron spectroscopy. They have pointed out that molecular autoionization of the $(LiHe)^+$ $2p\pi^2\,{}^1\Delta$ state is enhanced below 3 keV of Li^+-ion impact. Bringing the molecular autoionization into focus, we have measured the energy and angular distributions of the ejected electrons resulting from Li^+ impact on He. The impact energy E varies between 0.6 and 2.4 keV, and the electron-emission angle θ between 30° and 150° with respect to the incident Li^+ beam direction. The experimental apparatus and procedure are similar to those introduced by Yagishita *et al.*[2] The main change is an improvement of the Li^+-ion source to obtain a higher signal-counting rate at lower impact energies. The spectra observed include a peak due to a new type of interference among probability amplitudes of the ejected electrons. In the present Letter, the occurrence of this peak is discussed briefly, while a full and detailed account of the present measurements will appear in a subsequent paper.

