Pion Production in Heavy-Ion Collisions at $E_{\mathrm{lab}}/A = 35$ MeV

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Pion production was studied at $E_{\mathrm{lab}}/A = 35$ MeV in the reactions $^{14}\mathrm{N} + \mathrm{Al, Ni, W} \rightarrow \pi^0 + X$. Neutral pions were measured by detecting their two decay γ rays in coincidence in an array of ten Pb-glass Cherenkov-detector telescopes. The measured cross sections are much larger than predicted within the framework of independent nucleon-nucleon collisions and indicate that, at this energy, pion production is the result of cooperative action among many nucleons.

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In reactions between heavy ions free pions can be produced even at bombarding energies below the free nucleon-nucleon threshold either by use of the kinetic energy available from the Fermi motion in the projectile and target nuclei, or by a cooperative effect which coherently pools the kinetic energy of several nucleons.

Recent measurements[1,2] of inclusive pion production in heavy-ion collisions at energies between 60 and 84 MeV/u showed indications that the pions are produced by a source moving significantly more slowly than the nucleon-nucleon center-of-mass system, thus favoring the second possibility given above. Additional evidence comes from an analysis[3] of the observed cross sections and pion spectra.

If a cooperative process is indeed involved its importance for pion production must increase at lower bombarding energies. Indeed the sharp-cutoff Fermi model[4] cannot produce pions below 50 MeV/u. In addition, the collectivity in such collisions must increase with decreasing beam energy until, near the absolute threshold, pion production requires the coherent energy of all nucleons, thus leading to fusion of projectile and target (pionic fusion).[5] In contrast to the normal heavy-ion fusion and collision processes, pion production near absolute threshold requires concentration of most of the available energy of the center-of-mass system into only one degree of freedom, making pion production a unique probe for the very early, prethermalization stage of the collision.

In the present Letter we show that neutral pions are produced in heavy-ion collisions at bombarding energies as low as 35 MeV/u with cross sections more than three orders of magnitude greater than those predicted from Fermi-gas models.[3] This opens the possibility of studying the production process near threshold in some detail.

The experiment was performed with use of a 35-MeV/u ^{14}N beam with an average intensity of 3 particle nA produced by the $K = 500$ superconducting cyclotron at Michigan State University to bombard natural Al, Ni, and W targets, which had areal densities of 62, 90, and 98 mg/cm^2, respectively. With these thicknesses the beam lost less than 3 MeV/u in the targets. Neutral pions produced in these reactions were identified by detecting the two high-energy decay γ rays in an array of ten Pb-glass Cherenkov-detector telescopes. Each telescope consisted of a 5-cm-deep active converter with an area of 8.7×9.0 cm^2 backed by a 35-cm-long absorber with a cross section of 14.7×14.7 cm^2. High-energy γ rays (> 5 MeV) are converted into an electromagnetic shower in the F2 glass converters (radiation length 3.05 cm) which is then completely contained in the SF5 absorber blocks (radiation length 2.38 cm). Photomultipliers mounted on the top face of the converters and the back face of the absorbers detected the Cherenkov light produced by the shower, resulting in an energy resolution for the telescopes of $\sim 30\%$ at $E_\gamma = 100$ MeV. The ten telescopes were placed symmetrically in a plane on both sides of the beam direction at angles from 30° to 150° in 30° intervals, each telescope covering an angular range of approximately $\Delta\theta = 24°$. The energy scale of each absorber and converter was calibrated independently with cosmic-ray muons[6] both before and after the experiment. During the experiment, energy thresholds of ~10 MeV were set for each detector, and events of twofold or higher coincidences between any combination of telescopes were recorded on magnetic tape.

Neutral pions decay with 98.8% probability into two γ rays, on a time scale of 8.3×10^{-17} s. Thus, in the subsequent analysis twofold coincidence events were sorted into two-dimensional arrays of invariant mass $M_{\mathrm{inv}} = 2(E_{\gamma1}E_{\gamma2})^{1/2}\sin(\varphi/2)$ versus opening angle φ between the two telescopes (i.e., between the two γ rays). For true π^0 events M_{inv} should cluster around 135 MeV with a width determined by the γ-ray energy and angular resolution of the telescopes. The opening angle should fall in the range $90° < \varphi \leq 180°$ corresponding to π^0 kinetic energies between ~60 and 0 MeV. The top part of Fig. 1 shows such a scatter plot obtained for the system ^{14}N + ^{27}Al. Cosmic-ray background was reduced by setting a 10-nsec-wide time gate relative to the cyclotron cw beam pulses. The projection of the data onto the invariant-mass axis (bottom part of Fig. 1) shows a clean peak at the π^0 mass for the opening angles $\varphi \geq 90°$. Only a small background is observed for $\varphi < 90°$. The energy calibrations obtained from cosmic rays had to be rescaled by only a factor of 0.92 to correct the position of the observed mass peak to the known π^0 mass of 135 MeV.

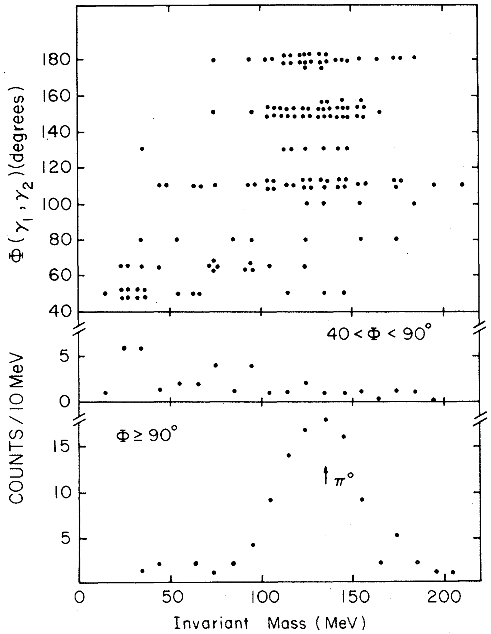

FIG. 1. (Top) Scatter plot of twofold coincidence events observed in the ^{14}N + ^{27}Al reaction in the plane of invariant mass and γ-ray opening angle. (Bottom) The projections on the mass axis of events with $\varphi < 90°$ and $\varphi \geq 90°$ demonstrate that π^0 events are clearly resolved from background.

The total efficiency of the detector array is the product of the geometric efficiency ϵ_g times the square of the probability ϵ_c of converting the photons in the converter blocks, i.e., $\epsilon = \epsilon_g \epsilon_c^2$. ϵ_g was obtained from detailed Monte Carlo calculations while ϵ_c is estimated from published data[7] to be between 0.5 and 0.8. The cross sections given in the present paper were calculated with use of $\epsilon_c = 0.7$. The systematic uncertainties in the total cross sections are therefore (+100, −30)% and are included in Fig. 4 only (see below). Random background due to cosmic-ray coincidences was determined by gating off the true time peak and by analyzing data taken with the beam off. The background cross section so deduced is approximately constant for $T(\pi^0) < 40$ MeV with upper limits of 0.12 and 0.20 nb/MeV for ^{14}N + Al and ^{14}N + Ni, respectively, and decreases to 0.05 and 0.14 nb/MeV at $T(\pi^0) \sim 70$ MeV. In view of the systematic uncertainties discussed above we have not performed any background subtraction.

Figure 2 shows the π^0 angular distributions and kinetic energy spectra in the laboratory system obtained from the bombardment of Al and Ni targets with ^{14}N. The resolutions ΔT_π and $\Delta\theta_\pi$ of

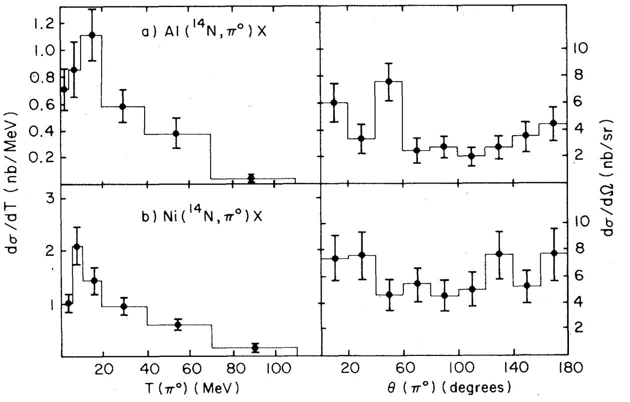

FIG. 2. Kinetic energy distributions (integrated over angle) and angular distributions of neutral pions (integrated over energy) relative to the beam axis observed in the reaction of 35-MeV/u ^{14}N beams with (a) Al and (b) Ni. The histograms indicate the bin widths, and indicated errors are statistical.

the setup are determined mostly by the angular resolution of the detectors since the pion kinetic energies predominantly depend[7] on the opening angle φ [see Eq. (1) of Ref. 7]. We have calculated these resolutions by Monte Carlo simulation and have chosen the binning in Fig. 2 accordingly. Further details will be presented elsewhere.[8] The energy spectra integrated over all angles are rather similar for both reactions with a peak near $T(\pi^0) \sim 10$ MeV and an exponential falloff towards higher kinetic energies. The measured angular distributions, integrated over all energies, indicate an anisotropy (at least for the system $^{14}N + ^{27}Al$), with a minimum near $\theta_{lab} = 90°$. Better statistics are required for a meaningful source-velocity analysis.

The total cross sections obtained for Al, Ni, and W targets are given in Fig. 3. The mass dependence of the inclusive π^0 production cross section follows an $A_T^{0.68}$ curve for the lighter targets but appears to saturate for heavier masses. A similar mass dependence had been observed at higher energy.[1, 2] The most interesting aspect is the unexpectedly large values of the cross sections: For the system $^{14}N + ^{27}Al$ the total inclusive π^0 production cross section is $\sigma = 42$ nb with a systematic uncertainty of (+42, −13) nb due to the poorly known absolute conversion efficiency ϵ_c.

Attempts to explain production at higher energy, but below the free nucleon-nucleon threshold, have used the Fermi-gas model. However, this model when applied with Pauli blocking and, more importantly, energy conservation[3] underpredicts the cross sections for $^{14}N + ^{27}Al \rightarrow \pi^0 + X$ by more than three orders of magnitude at $E_{lab}/A = 35$ MeV.

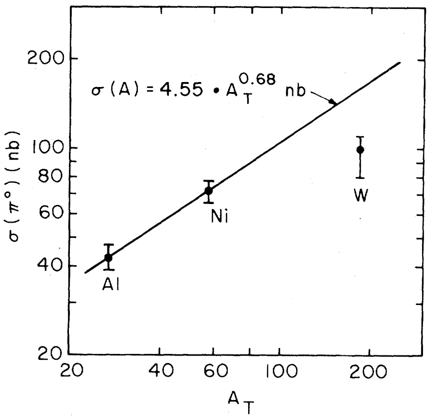

FIG. 3. Total integrated cross sections for inclusive π^0 production by 35-MeV/u ^{14}N beams on Al, Ni, and W targets. The target mass dependence of the cross section does not follow a simple power law, but the lower two points can be related by $A_T^{0.68}$.

To put these values into perspective it is useful to convert the present cross sections into equivalent values for the $^{12}C + ^{12}C$ system at the same bombarding energy by using the proportionality $\sigma \sim (A_{target} A_{project})^{0.68}$. Figure 4 shows our extrapolated value at 33.5 MeV/u (corrected for energy loss in the target) together with extensive earlier results at higher bombarding energies.[2]

Since models based on N-N collisions underpredict the measured cross section by at least three orders of magnitude, some cooperative effect, which pools the kinetic energy of several nucleons, must be involved. Such a phenomenon involving cluster formation in the final state is explored in Ref. 3. Microscopic models have been proposed[9-11] based on the excitation of a coherent delta nucleon-hole excitation. Another more

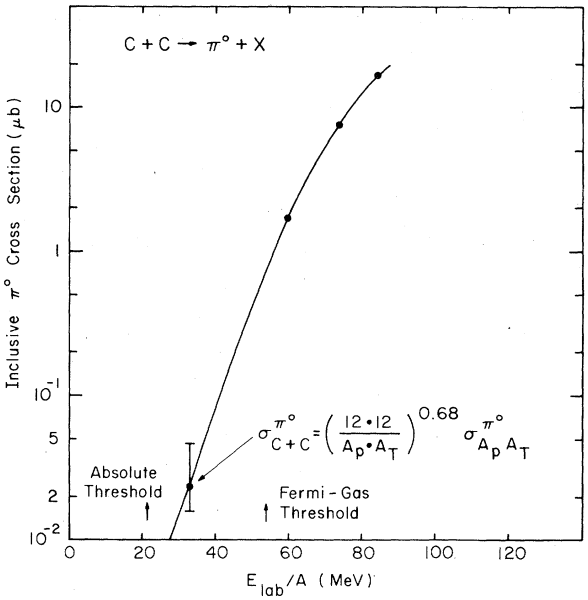

FIG. 4. Cross sections for π^0 production obtained at CERN (Ref. 2) and in the present experiment as a function of projectile bombarding energy. In order to unify data obtained in different projectile-target systems all cross sections are translated into the $^{12}C + ^{12}C$ system with use of the proportionality relation indicated in the figure. The indicated Fermi-gas energy threshold refers to a sharp-cutoff Fermi model (Ref. 4). Note that the absolute threshold is in the laboratory system. The curve drawn through the data points only serves to guide the eye. The error bar at 33.5 MeV/u includes systematic uncertainties as discussed in the text.

phenomenological model is that of pionic bremsstrahlung.[12] In this process the sudden slowing down of the projectile or parts of it, in the nuclear field of the target nucleus, on a time scale of 10^{-22} sec produces pions in close analogy to electromagnetic bremsstrahlung. More detailed measurements with improved statistics on angular distributions and energy spectra are presently being planned to specify the source of the pions.

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Note added.—After completion of the manuscript, we received a preprint by Aichelin and Bertsch in which pion production from the compound nucleus is investigated as an alternative mechanism.

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