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Pion Production in the $^{40}\text{Ar} + ^{40}\text{Ca}$ Reaction at 1.05 GeV/Nucleon

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Pion-production cross sections have been measured for the reaction $^{40}\text{Ar} + ^{40}\text{Ca} \rightarrow \pi^+ + X$ at a laboratory energy of 1.05 GeV/nucleon. A maximum in the π^+ cross section occurs at mid-rapidity, which is anomalous relative to $p + p$ and $p + \text{nucleus}$ reactions and compared to many other heavy-ion reactions. Calculations based on cascade and thermal models fail to fit the data.

In high-energy heavy-ion reactions it is generally believed that single-particle inclusive cross sections of π , p , d , t , etc., are dominated by simple factors such as geometry and energy-momentum conservation, and contain little information about the initial "compression" or early "expansion" stages of central or near-central collisions.¹ This may be attributed to the effect of averaging caused by large particle multiplicities, the acceptance of events from all impact parameters, and the rescattering of products due to very short mean free paths. For similar reasons, theoretical models using cascade,^{2,3} fire-streak,⁴ or hydrodynamic⁵ assumptions usually give semiquantitative agreement with particle-inclusive data.⁶ Therefore, it is interesting that in the present study of the $^{40}\text{Ar} + ^{40}\text{Ca}$ reaction at 1.05 GeV/nucleon, the π^+ emission pattern is peaked in the mid-rapidity region, which is not predicted by theoretical calculations and is unique compared to $p + p$ and $p + \text{nucleus}$ reactions and heavy-ion reactions at lower bombarding energies. Because of this unusual behavior, the possibility must be considered that the structure in the π^+ cross section near 90° in the center-of-mass system may be a signature of processes from an early stage of the reaction which has not been fully averaged out.

One can understand how such information might survive in this particular instance for low-energy pions produced in a rather light system. Because of a large energy threshold, pions are produced preferentially in regions of high density and tem-

perature or from particularly violent nucleon-nucleon collisions, with little contribution from spectator deexcitation. Furthermore, since these pion energies near 90° in the c.m. system are well below the $\Delta(1232)$ resonance energy, it is expected that the mean free path is comparable to the dimensions of the $^{40}\text{Ar} + ^{40}\text{Ca}$ system, allowing an appreciable amount of unattenuated pion emission.

A beam of ^{40}Ar ions at 1.05 GeV/nucleon from the Lawrence Berkeley Laboratory Bevalac was used to induce reactions in a 200-mg/cm² Ca target. Pions were identified and the energy spectra were measured over a range of 15–95 MeV with a multielement dE/dx telescope¹ consisting of a 5-mm Si(Li) crystal, and 28- and 42-mm intrinsic germanium crystals with a Si(Li) reject counter. A delayed-coincidence technique was applied to identify stopped π^+ by observing the positrons from the subsequent muon decay in the germanium crystals of the detector, from the decay sequence $\pi^+ \xrightarrow{25 \text{ ns}} \mu^+ \xrightarrow{2.2 \text{ } \mu\text{s}} e^+ + \nu + \bar{\nu}$. Pion energy spectra were corrected for absorption, multiple scattering, and the inefficiency of detecting the positrons produced in the muon decay. The systematic uncertainty in the π^+ cross sections is estimated to be $\approx 30\%$ with a precision better than 10%. In addition to the pion-inclusive measurements, the associated charged-particle multiplicity was determined on an event-by-event basis, allowing a type of impact parameter selection.¹ The multiplicity was measured with an 80-counter array of plastic scintillators coupled to

photomultiplier tubes and discriminators. The array covered 67% of the forward hemisphere and was sensitive to p , d , t , etc., with energies greater than ≈ 25 MeV/nucleon and charged pions with energies greater than 10 MeV.

The measured π^+ energy spectra are shown in Fig. 1 along with the results of an intranuclear cascade calculation, using the code of Fraenkel and Yariv,³ and the predictions of the firestreak model of Gosset, Kapusta, and Westfall.⁴ These two models represent very different assumptions about the reaction. The cascade calculation approaches the problem as one of simple nucleon-nucleon collisions, using a pure isobar model for pion production and absorption. In the nuclear firestreak model it is assumed that in the overlapping region of the target and projectile nucleons, thermodynamic and chemical equilibria are established among the hadrons, with an isobaric expansion to the freeze-out density, here assumed to be 0.12 hadron/fm³. It can be seen in Fig. 1 that neither model gives a satisfactory fit to the data, differing by factors of $\approx 2-3$ at the extreme ends of the measured spectra. This cannot be considered reasonable agreement if we are to take these models seriously.

The anomalous nature of the pion emission in the $^{40}\text{Ar} + ^{40}\text{Ca}$ reaction is perhaps better demonstrated in Fig. 2(a) by comparison with other experimental data and by transforming the data to

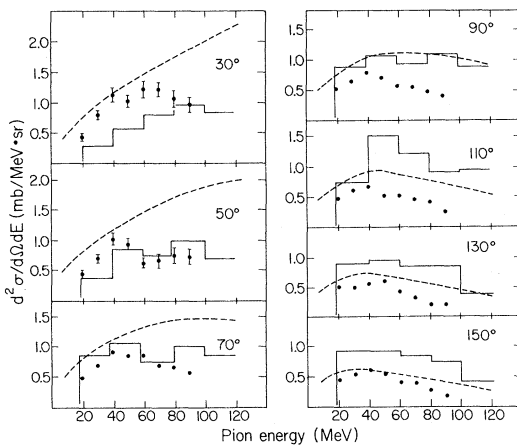


FIG. 1. Pion-inclusive double differential cross sections in the laboratory system for the reaction $^{40}\text{Ar} + ^{40}\text{Ca} \rightarrow \pi^+ + X$ at 1.05 GeV/nucleon. Statistical errors are smaller than the size of the points except where indicated. The histograms (solid lines) show the results of a nuclear cascade calculation (Ref. 3) and the dashed lines represent a nuclear firestreak calculation (Ref. 4).

a "rapidity plot" which is generally useful in obtaining qualitative information about emission sources of particles. The most prominent feature of Fig. 2(a) is the enhanced pion yield at mid-rapidity, i.e., at the center of mass of the target-projectile system, and at a perpendicular momentum of $\approx 0.4m_\pi$ (≈ 55 MeV/c). The only other target-projectile combination studied to date which exhibits similar structure in the pion spectra is the reaction⁷ of 800-MeV/nucleon $^{20}\text{Ne} + \text{NaF}$. This structure is not seen at lower energies, such as in the 400-MeV/nucleon $^{20}\text{Ne} + ^{27}\text{Al}$ reaction,⁸ but it is not known whether this is a real change in the phenomenon, or if the small separation between target and projectile rapidities masks the effect.

A cross-section pattern like that shown in Fig. 2(a) is quite unexpected. In a fireball model, pion emission is isotropic in the c.m. system of an equal-mass collision with an exponentially decaying energy spectrum,⁴ creating nearly semi-circular contours centered at mid-rapidity and at $p_\perp = 0$. For a nucleon-nucleon collision picture, we may use the cascade calculation of Fig.

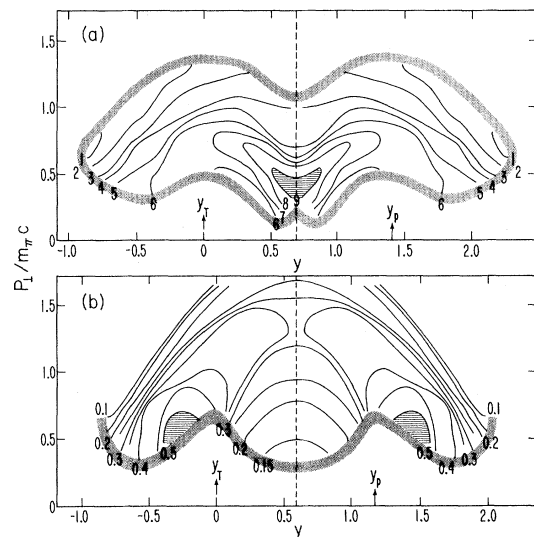


FIG. 2. Contours of constant Lorentz-invariant pion cross section, $(1/p)d^2\sigma/d\Omega dE$, in units of $b/(\text{sr GeV}^2/c)$, as a function of perpendicular pion momentum and rapidity, y . (a) Results of the present study for 1.05-GeV/nucleon $^{40}\text{Ar} + ^{40}\text{Ca}$; (b) constructed from data for the $p + p$ reaction (Ref. 9) at 730 MeV. Both sets of data have been reflected through mid-rapidity, $(y_p + y_T)/2$, shown by the dashed vertical lines. The areas within the maximum contours have horizontal shading. The shaded edges indicate the limits of the experimental measurements.

1 for $^{40}\text{Ar} + ^{40}\text{Ca}$, which gives qualitatively the same results as for the pion-inclusive data of Cochran *et al.*⁹ for the $p + p$ reaction at a slightly lower beam rapidity, plotted in Fig. 2(b). The $p + p$ data can be understood in terms of the decay of an isobar nearly at rest in the center of mass. The characteristic forward-backward peaking with a pion momentum of ≈ 230 MeV/c shows little similarity to the $^{40}\text{Ar} + ^{40}\text{Ca}$ data. In particular, the $p + p$ reaction has a very small pion yield at mid-rapidity (90° c.m.) and at $p_\perp \approx 0.4 m_\pi$. Similarly, only small pion yields are observed in this region for $p + \text{nucleus}$ reactions,^{8,9} which may be expected to show effects associated with the Fermi motion, and with pion absorption and scattering. But reactions of unequal target and projectile masses do not have a unique center of mass of the participants, making interpretation difficult. It is unlikely that pion attenuation is important for the $^{40}\text{Ar} + ^{40}\text{Ca}$ reaction, because of the long mean free path expected in the energy range of interest here.¹⁰ Also, we investigated the effect of gating on high charged-particle multiplicities in order to select more central collisions.¹ If attenuation effects were important in the participant or spectator regions the change in shadowing geometry accompanying this impact-parameter restriction should alter the emission pattern, as seems to be the case for ^{20}Ne - and ^{40}Ar -induced reactions on heavy targets.⁸ Chiba *et al.*,⁷ who did not measure associated multiplicities, attributed the peak in the $^{20}\text{Ne} + \text{NaF}$ system to such secondary processes or rescattering effects. Because we have multiplicity selection, we can show that this possibility is unlikely since the peak is independent of the sizes of the interaction region and the spectator pieces. This is shown by the spectra in Fig. 3 where no significant change is observed for a restriction of the impact parameter to less than an estimated 4 fm, compared to a grazing distance of 8 fm. This seems to hold for both the spectral shapes and angular distributions, in the mid-rapidity region near 90° at $p \approx 200$ MeV/c where isobar decay should contribute.

The lack of an impact-parameter dependence of the spectral shapes is expected in a fireball model for an equal-mass target-projectile reaction because all impact parameters result in the same forward momentum and temperature for the participants. However, a sideways-peaked c.m. angular distribution cannot be explained, which is an especially significant shortcoming of the thermal models for low-energy pions with small

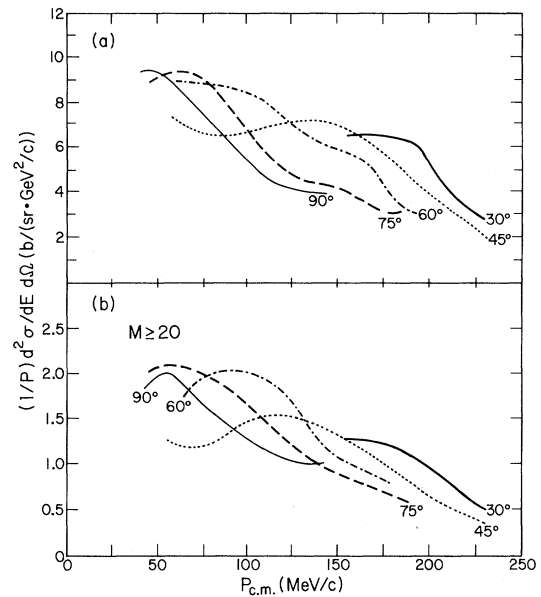


FIG. 3. Invariant cross section as a function of momentum for the center-of-mass angles 30° , 45° , 60° , 75° , and 90° . (a) π^+ inclusive cross sections. In (b) the detected π^+ were coincidence gated by the requirement that at least twenty charged particles were detected in the multiplicity array, corresponding to the upper 15% of the multiplicity distribution.

shadowing effects. Also the measured energy spectra fall off much more rapidly at high energy than is predicted. Qualitatively the energy spectra can be accounted for by lowering the temperature of the emitting fireball, for instance, by early emission of pions or by adding a compression energy term to the fireball model.^{11,12} The angular distribution is more difficult to explain and hints strongly at collective, hydrodynamic flow effects¹³ to account for the preferential sideways ejection of pions observed here.

Coulomb repulsion in the π^+ -nucleus system may be partially responsible for the broad maxima in the 75° and 90° spectra of Fig. 3, but cannot account for the rapid falloff at high momentum, and for the fact that the corresponding cross section maximum occurs at a slightly *higher* momentum in the lighter $^{20}\text{Ne} + \text{NaF}$ system.⁷

In summary, π^+ -inclusive data for the $^{40}\text{Ar} + ^{40}\text{Ca}$ reaction at 1.05 GeV/nucleon are found to have some striking features compared to other target-projectile combinations. A rapidity plot of the data shows an enhanced pion yield centered at mid-rapidity, forming a unique pattern which is insensitive to multiplicity selection. Poor fits to the data indicate that this effect is not account-

ed for in the thermal and cascade models.

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g Factors of High-Spin Yrast Traps in $^{146,147}\text{Gd}$

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Pulsed beams of ^{28}Si and ^4He were used to determine g factors of eight isomeric states in $^{144,146,147,148}\text{Gd}$ by the time-differential spin-rotation method. The results show that proton and neutron configurations contribute about equally to the generation of angular momenta of two high-spin yrast isomers in $^{146,147}\text{Gd}$ ($I \sim 19$ and $49/2$) whose detailed quasi-particle structure is suggested.

After the initial discovery¹ of an "island" of high-spin isomers in nuclei near the neutron shell closure at $N = 82$, considerable progress has been made in identifying individual yrast states up to very high spin. The excitation energies of these states with spins $14 \lesssim J \lesssim 36$ in ^{152}Dy (Ref. 2) and ^{154}Er ,³ when plotted versus $I(I + 1)$, follow very closely a straight line characterized by an effective moment of inertia close to,³ or larger than,² that for a rotation of a rigid sphere.

Very recent lifetime measurements⁴ in ^{152}Dy have demonstrated that the reduced $E 2$ probabilities for transitions between yrast states are strongly inhibited relative to typical rotational values, indicating that these transitions involve rearrangements of single-particle orbitals.⁵

The more detailed structure of the high-spin yrast states can best be investigated by measurements of g factors since these depend on the coupling scheme for the individual particles, particu-